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AL, A PROGRAMMING SYSTEM FOR AUTOMATION

BY

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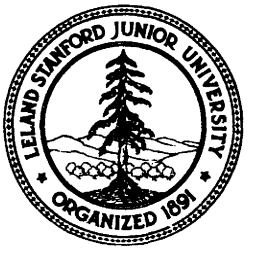

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AL, A Programming System for Automation

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AL is an high-level programming system for specification of manipulatory tasks such as assembly of an object from parts. AL includes an ALGOL-like source language, a translator for converting programs into runnable code, and a runtime system for controlling manipulators and other devices. The system includes advanced features for describing individual motions of manipulators, for using sensory information, and for describing assembly algorithms in terms of common domain-specific primitives. This document describes the design of AL, which is currently being implemented as a successor to the Stanford WAVE system.

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This document describes the new hand language, AL. It is not intended to be a final language specification or a user's manual. Rather, it is a working document presenting a number of related ideas concerning a system for programmable automation. These ideas cover a broad range of topics: arm servoing, parallel processing, assembly world modelling, strategists, and language design. We have tried to combine these into a coherent system. However, as you read this document you will notice that some topics have been explored more than others, some explanations contain more detail than others, and some questions are left unanswered. Various portions of the system have already been implemented.

Interested persons unfamiliar with the background for this work will find it useful to read *The Use of Sensory Feedback in a Programmable Assembly System* [Bolles and Paul].

We would like to thank those people who have made numerous suggestions and have helped implement various parts of the system. In particular,-we would to thank Bertrand Meyer, who implemented the scanner and parser, Botond Eross, who is implementing the PDP11 runtime monitor, Bruce Baumgart, who assisted with the illustrations, and Larry Tesler, whose document preparation program PUB was used to prepare this paper. We also wish to thank D. Whitney, J. Nevins, and D. Killoran of Draper Labs and W. Park of Stanford Research Institute for their helpful criticisms and suggestions.

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The English language has no genderless personal pronoun; without any implication of sexism we use arbitrary forms in its place.

CHAPTER 1
AN OVERVIEW OF AL

1.1 INTRODUCTION

The development of robot manipulators such as the "Unimate" has led to the belief that these tools are in some way general-purpose devices and that they might be programmed like a computer. As a general-purpose programmable device, the robot manipulator would provide an answer to the need for automation of assembly in batch manufacturing industries where small production runs rule out the use of special-purpose-equipment to increase productivity.

This document describes a new manipulator programming language, "AL" which is being implemented as a successor to the WAVE system developed at the Stanford Artificial Intelligence Laboratory during the last 5 years.

The aim of this work is not to provide a "hands on" factory floor programming system but rather an experimental laboratory tool for investigating the difficulty, necessary programming time, and feasibility of writing programs to control assembly operations.

We are designing a system for small scale batch manufacturing where setup time is the key factor. We will rely on a symbolic database and previously defined assembly primitives to minimize the programming time. The system will be capable of top level planning and the intelligent interpretation of user defined primitives.

The batch manufacturing environment is fairly structured; we will make use of this fact to do as much computation as possible before an assembly begins. Such computation can be done offline and in connection with the data base; during this phase, time will be spent optimizing each operation, By performing this computation prior to the assembly, the amount of computation that the robot must perform for each assembly is reduced.

Unlike WAVE, which followed a machine-language-like programming style with skips and jumps, AL is a highly structured language with control structures resembling those of Algol. The facility to work in many different coordinate systems and to evaluate general expressions is added. The new language will provide for the simultaneous control of more than one robot either asynchronously or cooperatively. Macro-like routines may be defined to express general-purpose assembly primitives which will be conditionally expanded at compile time. Additional data may be added to these routines to enable a top level strategy program to use these routines to accomplish entire assembly operations.

The language will allow a task to be specified at several different levels of detail, ranging from very explicit and detailed manipulator control programs to programs written in terms of "high-level" assembly operators which the system will then translate into manipulator control programs. When used in this latter mode, the system makes extensive use of its planning model, together with a progressive refinement strategy in order to produce a consistent and efficient output program.

The system itself is written in the high level language "SAIL" to facilitate modification and change. We expect to modify the language on a day-to-day basis as we start to use it and gain experience. We will implement the language as it is defined in this document, and based on experience we will modify it to obtain a better system.

1.2 PHILOSOPHY AND DESIGN COALS

A full language for planning manipulatory tasks of the complexity required for assembly needs many features, some of which do not exist in any current system. We have identified the following interrelated goals.

1.2.1 DATA AND CONTROL STRUCTURES

We believe that the principal mode of input to AL should be textual, as opposed to spoken or manual (joystick). There are levels of complexity which are much more readily transmitted from man to machine through an interface of symbolic text. Complicated simultaneous motions of two arms and specifications of termination and error conditions are more likely to be unambiguously stated through the medium of text, if for no other reason than the structure imposed on the textual language forces a consistent framework on initially less structured intuitive ideas. Non-textual forms of input can be a very useful means for defining target locations, suggesting arm trajectories designed to avoid collisions, and other purposes of this nature. We believe, however, that such tools are most useful when applied in conjunction with a program text which supplies the skeletal intent of the programmer; to this end AL should facilitate use of such input devices as joysticks and other positioning tools during the process of programming.

The supervisor level of AL should be simple enough to allow natural teaching by showing; it should be easy to interface such new devices as joysticks and simple vocal input into AL, although we do not intend to do so at present.

We want to write entire programs in a natural manner. The machine-language aspect of current manipulation languages makes it cumbersome to write long programs in any structured way. We want a language which lends itself to a more systematic and perspicuous programming style. Algol-like control structures are an improvement over assembly-like straight code with jumps.

Experience with languages like SAIL and WAVE has shown that text macros are a useful feature; they reduce the amount of repetitive typing. AL should have a general-purpose text macro system interfaced into the scanner and parser.

The datatypes available should include those types necessary to refer to one-dimensional measures (like distance, time, mass) and three-dimensional measures (like directed distance, locations, orientations). Arithmetic operators should be available not only for the standard scalar operations like multiplication and addition, but also for such operations as rotation and translation.

Simultaneous execution of several processes should be available. A general mechanism for simultaneity is desired, so that calculation and arm motion can take place simultaneously, and several manipulators can be in independent motion.

1.2.2 MOTION SPECIFICATIONS

Experience with WAVE has shown that calculating trajectories for manipulators is a desirable feature, although a time-consuming one. Trajectory calculations, together with **all other** calculations which need only be performed once, should be done at compile time. This allocation of effort can drastically reduce the computing load at execution time and eliminate wasteful recomputation every time a sequence of actions is executed. This leads to a clear distinction between compile-time and **runtime.**

The user should be able to demand that a trajectory pass through given intermediate points. The primary use of this is to avoid collisions during the motion. It is also useful in specifying complicated motions.

A wide range of exceptional conditions can occur during the motion of a manipulator: excessive force might be exerted, a stopping condition may be met, the arm might come too close to a dangerous region, the user may interrupt the motion manually, or some specified time limit might be exceeded. Appropriate action must be taken as soon as any of these occurs, for example: to start up a new concurrent process, to terminate something already active, to notify the user, to file away a statistic somewhere in a table. Therefore, AL must allow the user flexibility in specifying what conditions to monitor during the course of motions (and during execution of blocks of code in general), and what to do in the case that a tested condition occurs. It is also useful to change the nature of the test during a motion, if different segments of the motion require different types of monitoring. This concept can be generalized to include the modification of a motion during its execution to **accomodate** to changing conditions.

We make the assumption that threshold tests suffice for assembly with sensory feedback. In many cases, threshold tests do suffice: To tell if the arm has hit something, a threshold test on directed force works. To tell if a screw is binding, a similar test serves. In general, however, such tests lack the ability to modify trajectories on the basis of signal strength. This lack is only partially filled by an ability to disable and enable condition monitors during the course of a motion. It is our hope **eventually** to include the capacity for including devices such as wrist force sensors and vision in the servo control loop in a programmable fashion. When these fascinating prospects are better understood, they will be included in the language.

1.2.3 USE OF A PLANNING MODEL

Since locations are not known exactly during the planning of a trajectory, there should be a clear distinction between planned values and **runtime** values. Planned values will be used for trajectory calculation; at **runtime,** trajectories will be modified if necessary to account for any discrepancies. The planned values are therefore a database on which trajectory calculations are computed. This database will occasionally be referred to as a ***world*** *model.*

Assembly tasks require that one object be affixed to another. We wish to model this by having a semantic attachment between objects. If two objects are affixed, and one moves, the second one should move accordingly, that is, its planning value should be properly modified. Thus, the world model must also include information on attachments of objects, since they will have an effect on planning values. The affixment concept carries over to the **runtime** system, which does the equivalent modifications of the actual values. This saves the user untold bookkeeping operations to determine where an object is after its base has been moved.

More generally, the compiler should be able to maintain a wide variety of information about expected **runtime** states. This includes not only object affixments and variable planning values, as previously mentioned, but also information like the accuracy within which the planning value is known, how heavy an object is, how many faces it has on which it can rest, how wide the fingers of an arm should open to grasp it. This information may come from several sources, including explicit assertions by the user, the output-of computer-aided design programs, and built-in knowledge about the system hardware. Therefore, AL should have a general framework for representing such knowledge.

In addition to its own internal uses, AL should provide a number of explicit mechanisms for applying this information, including simple retrieval of data from the compile-time model and conditional compilation facilities for producing substantially different object programs, depending on planning information. Such facilities allow the user to write a single piece of code in some generality, while avoiding the inefficiencies of many needless **runtime** checks and the planning of useless trajectories for cases that will never be executed.

1.2.4 USE OF DOMAIN-SPECIFIC KNOWLEDGE

The system should have enough domain-specific knowledge to allow programs to be written in terms of common assembly operations, rather than exclusively in terms of detailed single motions. At the simplest level, this involves provision of a library of common assembly "macro-operations" that can be conditionally expanded to perform particular subtasks. Beyond this, we **would** like an interactive system that can take a "high level" description of an assembly algorithm and fill in many of the detailed decisions required to produce a consistent and efficient output program.

The range of decisions required to convert from-a high level description to an efficient output program is quite broad, and many of the processes involved cannot be **modelled** readily in terms of the purely local mechanisms used in expanding library routines. For instance, a command like "put the engine block on the table in an upright position" might require the system to examine future operations on the engine block to select the best orientation to use. Similarly, many operations produce side effects that make other tasks either easier or harder. For instance, inserting a pin into a hole yields information about the exact location of the hole and therefore of the object into which the hole has been drilled. If there are a number of pins to be inserted, then it may be a good idea to insert pins into the easier-to-locate holes first and then to use the information so gained to help with the remaining insertions. (On the other hand, such an ordering may very well make the actual insertions more difficult because of obstructions to the hand). The system should be familiar with such considerations and use them as it generates the output program.

A user should be able to specify different parts of a task at various levels of detail. The system must be able to accept explicit advice telling exactly how some particular **subtask** is to be accomplished and then complete the program in a way that does not conflict with those things that have been explicitly specified. This is especially important for early versions of AL, which are not likely to be very "smart" and will therefore require a fair amount of explicit help.

The user should be able to describe the "intent" of a particular piece of code, at least to the extent of specifying any (non-obvious) prerequisites or updates to the world model. This facility is especially important for programs that mix both high and low-level primitives. Similarly, the system should be able to show the user how it is filling in the details to produce an output program, and why. This is very important both for debugging and for explaining to the user any requests for advice that it must make.

1.2.5 THE RUNTIME SYSTEM

The calculation of trajectories is time-consuming but not time-critical; servoing of devices is time-critical but not especially time-consuming. For efficient code generation, modification, documentation, and execution, we will write the compiler in a high-level language and develop and run it under time-sharing. The **runtime** programs will be written in either machine language or one of the new systems implementation languages (for example, BLISS), since time-efficient code must be generated. As one execution computer will be required for each work station in a factory, and as the **runtime** code and its memory requirements will be quite small, we will write the **runtime** system for a minicomputer. The compiler could also be written for the small computer, but this would compound the problems of writing the compiler; the computational requirements are much higher during compilation than execution, so implementing the compiler on the mini would necessitate either an overly large minicomputer or an overly slow compiler.

The **runtime** system must support simultaneous executions of many processes. Several manipulators or devices might be running simultaneously, and each motor requires a separate process; several condition monitors might be active; several code segments (doing, perhaps, calculations) might be simultaneously active. Those processes which are dealing with real-time devices (joint servos and condition checkers) must be guaranteed service at regular intervals; the computation processes can fill in. any time gaps. Thus, the **runtime** system must include some simple implementation of multiple processes under real-time constraints.

Trajectories are calculated by the compiler on the basis of incomplete information. At **runtime,** it is necessary to modify those plans to fit them to the somewhat different actual location of objects. That means that certain information must be carried at **runtime,** specifically the locations that each trajectory is desired to pass through, the locations of all objects, and how they are attached together.

The system must be capable of using vision and other currently unimplemented forms of feedback. Vision would be quite useful in searching for objects and testing for adequacy of assembly. It is conceivable that vision will be used for the servoing of an arm; this implies that vision would be in the feedback loop during motions. Other dynamic feedback (like force-sensing wrists) could make the capabilities of the arms much greater in dealing with non-rigid materials

like cloth or rope. What is needed is a way of specifying these "external" devices so that when they become available, they can be meshed into the system without much difficulty.

The wide range of conceivable tasks implies that pure hardware servoing will not in general suffice. The reason for this is that hardware servoing restricts use to one of a small number of servo modes (typically position, velocity, or force), and has no provision for motions of accomodation or motions whose modes might change in midstream due to some software-detectable condition. Pure hardware servoing could not be readily modified to account for new feedback devices or methods. A philosophy of *software servoing* has these advantages: It is possible to program the manner in which feedback is to be used, to interface new types of sensors, to modify the servo while the arm is in motion, to supply the driving program with information concerning the success of the motion as well as to keep it up-to-date on the arm status. Some clearly distinguishable modes of servoing could be translated into hardware; however, the hardware becomes complicated if the computer needs to be able to switch modes while the program is being executed. There would not be much saving in compute power since the computer would need to perform a servo calculation in order to understand what the manipulator is doing and to interact with the task.

1.26 PROGRAMMING AIDS

A user should be able to write a piece of code, try it on the spot, and delete or replace sections of previous code.

The compiler should make a great number of semantic checks, such as assuring that a proposed motion will not hit some object (although this is a difficult problem which has not yet been satisfactorily solved) or that simultaneous independent motions are not being requested for the same device.

AL should eventually include non-textual aids to programming. For example, joysticks might be used to position heavy manipulators prior to reading their locations and using them in a program. Graphical display could be used to to demonstrate the planned locations of objects and how this changes during the course of the program.

Error recovery facilities are very important. A user should be able to recover from errors discovered during any phase of debugging. Similarly, production programs should be able to request operator intervention where necessary and should (at least) be able to be restarted at a convenient place after the problem is fixed.

There should be a way to investigate the contents of the runtime system, both variables and code, in order to patch simple mistakes discovered during the course of a production run. This feature will be especially useful for debugging the compiler.

1.3 GENERAL SYSTEM OUTLINE

The actual version of AL which we will implement is related to our current hardware and software capabilities. The following sections describe the overall system from a general point of view.

1.3.1 HARD WARE

Currently two Stanford Electric Arms, built by Victor Scheinman [Scheinman], are available. They are called YELLOW and BLUE. Each has six joints and a hand that can open and close. The joints are controlled by electric motors; each joint has both position and velocity feedback. Motor drives are sent from the computer to the arm via a digital-to-analog converter (D-to-A); feedback signals are routed through an analog-to-digital converter (A-to-D) back to the computer.

There are two computer-controlled cameras. The computer can control the pan, tilt, focus, iris, filter, and zoom (or lens turret) on each camera.

Various others devices are designed and implemented as needed. We use tools, jigs and special markings for several purposes: to render a task possible (an example is the arm itself), to improve efficiency (the mechanical screwdriver), and to overcome some of our sensory and mechanical limitations (the screw dispenser). Currently we have an electrically powered screwdriver, a pneumatic vise, and an electrically controlled turntable. The screwdriver can be picked up by an arm and operates in either direction over a range of speeds. The vise can be opened or closed; soon there will be a way to servo it to a specified opening. The computer can position the turntable to any rotation (within .5 degrees). As such devices are built, they will be interfaced to the A-to-D, the **runtime** programs told how to control them, and the language extended to include syntax to describe how to use them.

AL resides on two computers: The PDP-10 for all planning, and a PDP-1 1/45 for the execution of the plans. The former is run as a timesharing computer (under a modified DEC system); the latter is operated in stand-alone mode under the AL **runtime** system. Each computer is capable of generating an interrupt in the other, and the PDP-10 has complete control over the PDP-11 console and unibus. It is not certain exactly-what the minimum **runtime** computer configuration will be; we use floating point and memory management, but it is not clear that this is altogether necessary.

1.3.2 SOFTWARE

See Figure 1.1 for a picture of the system.

The SUPERVISOR is the top level of AL. It runs on the timesharing computer and provides an interface between the user and the other parts of the system: 1) listening to the user's console and interpreting input in a simple command language; 2) controlling the compiler, starting it and

relaying its error messages back to the user; 3) signalling the loader when it is necessary to place compiled code into the mini; 4) handling the runtime interface to the mini. Each of these subsidiary modules is discussed below.

The USER sits at a console and makes requests of AL. These fall into several categories: compilation, loading, execution of programs, debugging of code, requesting of status information, asking for immediate arm motion, saving and restoring the state of the world at safe points, requesting explanation of certain compiler decisions. There are two different consoles at which a user can sit: one is connected to the timesharing computer, through which she can speak to the supervisor and all the parts of AL residing on the timesharing computer; the other is connected to the mini, and through it the user can investigate the runtime system and cause modifications.

The COMPILER reads AL programs from files (or, optionally, directly from the user's console) and produces load modules. The compiler is divided into three phases: The PARSER, the EXPANDER, and the TRAJECTORY CALCULATOR. The compiler is discussed in detail in the next section and is pictured in Figure 1.2.

The LOADER takes the load modules prepared by the compiler and enters them into the mini's runtime system. Address relocation and linking are done at this time. The loader also sets up the data area in the runtime interface in the timesharing computer; this data includes output strings, procedure linkages, and information necessary for diagnostic purposes during runtime. Loading is often done in a partially incremental fashion, installing new code following previously loaded code.

The RUNTIME INTERFACE, which resides in the timesharing computer, is charged with initiating the mini program, fielding procedure calls from the running program to procedures on the timesharing machine, returning values from these procedures, and fetching values from the mini for debugging purposes. The interface has the power to interrupt the execution of the program and to modify the status of the runtime system, for example, by patching in additional program, or modifying the values of some variables. This allows the user to control the program through the timesharing computer.

The RUNTIME SYSTEM is the set of programs which reside in the mini. This system includes kernel programs for time-slice cpu sharing and process control and a set of dynamically created p rocesses. These are of three basic types: a) An INTERPRETER examines the code prepared by the compiler and executes the numeric computations requested. When a move is to be started, the interpreter creates a servo for each joint and waits until all these servos are finished. b) A SERVO handles the motion of one moving joint. c) A CONDITION-MONITOR repeatedly examines certain conditions (whatever the programmer has specified). If it should discover that its condition has occurred, it creates an interpreter to take appropriate action. The runtime system also includes routines for communication with the runtime interface in the timesharing computer.

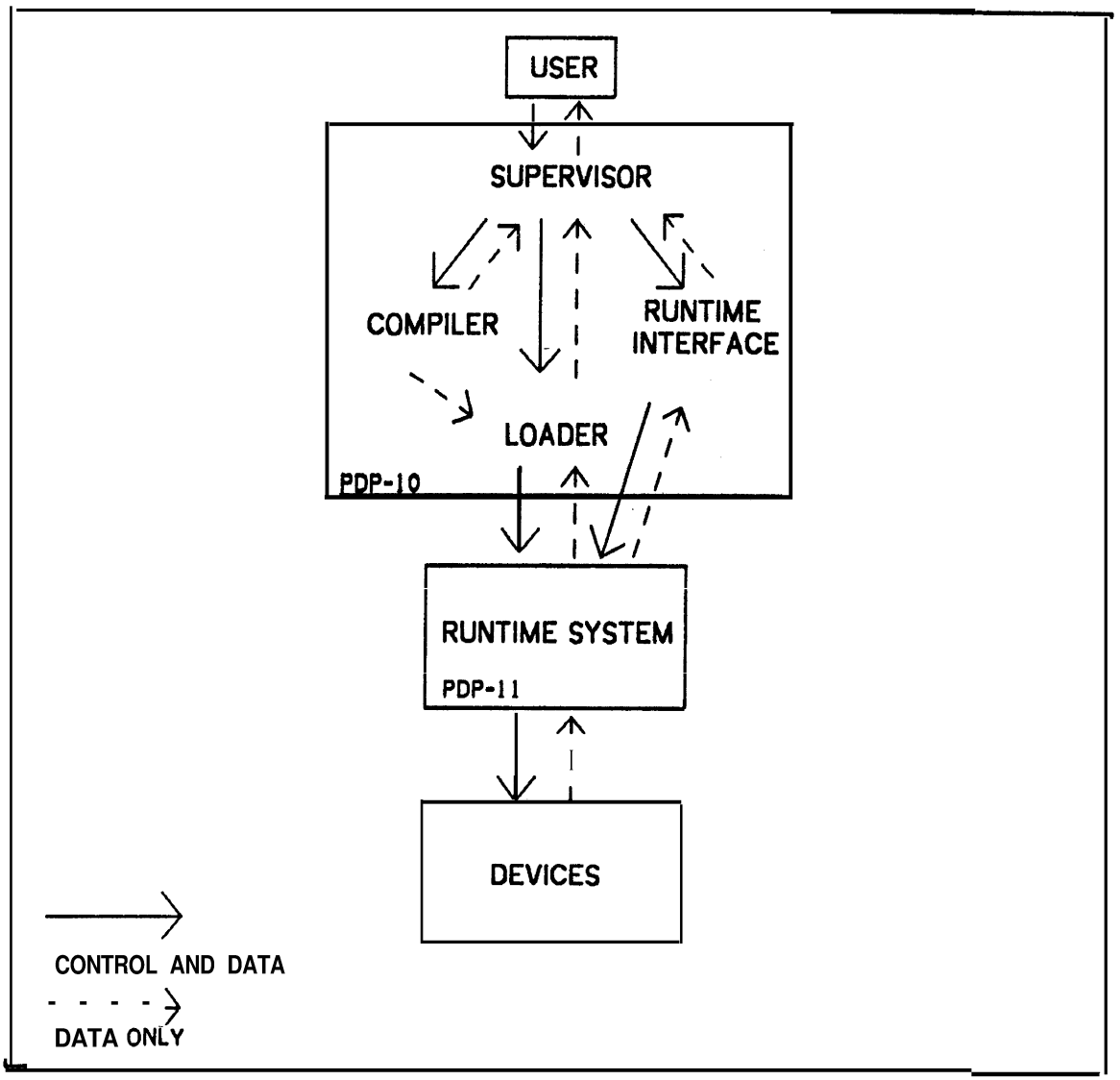

Figure 1.1
Overall system

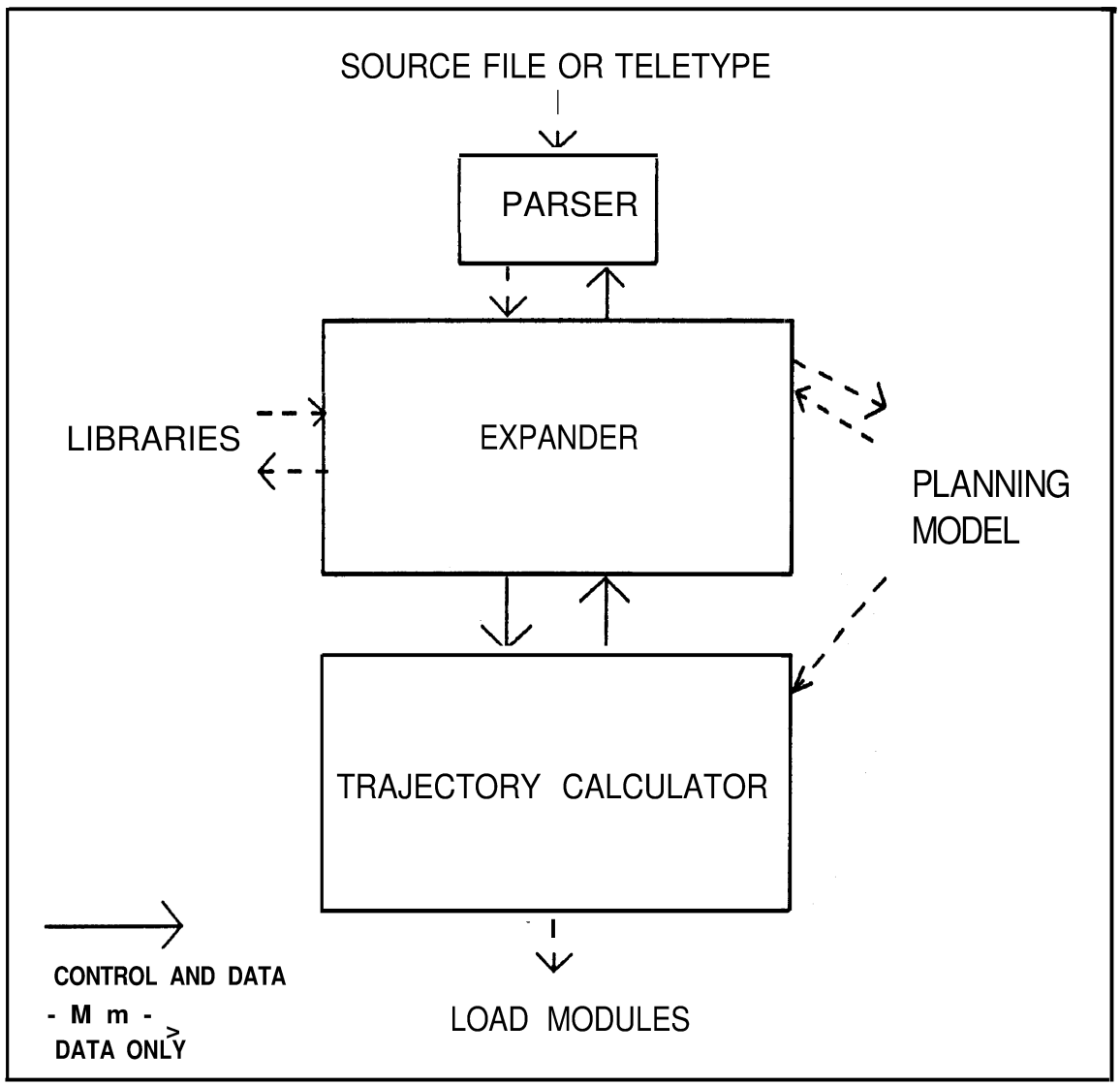

Figure 1.2
The 'AL compiler

1.4 THE AL COMPILER

The AL compiler is built of three parts: the parser, the expander, and the trajectory calculator. These are depicted in Figure 1.2.

1.4.1 PARSER

The PARSER reads source code from either the console or a file. Its purpose is to form parse trees and do some simple manipulations, such as assigning line numbers, causing listings to be directed to the appropriate file (if desired), expanding text macros, and keeping a primitive symbol table. If a syntax error is discovered, it informs the supervisor, which will give the user several options, including aborting the compilation, making local modifications on the spot, or switching temporarily to a text editor.

1.4.2 EXPANDER

The EXPANDER shares with the trajectory calculator the responsibility for turning parser output into code interpretable by the **runtime** system. Its main functions are to maintain a model of the expected **runtime** state at each point in the program and to use this model to resolve a number of compile-time decisions. The information kept includes planning values, object descriptions, relations between objects, endpoint constraints on particular trajectories, and much **more**. Simple uses of this information include providing the trajectory calculator with essential data and resolving conditional compilation requests. Beyond this, the expander has principal responsibility for filling in the details required to turn calls on various high and intermediate level primitives into runnable manipulation programs. It therefore contains a number of quite specialized routines with considerable knowledge about the domain of mechanical assembly, as well as a number of more general mechanisms for coordinating the specialists.

The expander supplies to the trajectory calculator a structure which is very similar to the parse trees it accepts as input. However, no choices are left; all values have been explicitly specified.

1.4.3 TRAJECTORY CALCULATOR

The TRAJECTORY CALCULATOR takes the expanded code and computes the required trajectories for the arms. Tables of interpretable code are generated for handling arithmetic and assignment operations, condition monitoring, and affixment structure building operations (the **runtime** system keeps track of physical attachment of objects). For motions, detailed tables are emitted specifying how each joint of each arm is to behave, what computations to make at **run-**time for the modification of these trajectories to bring them into correspondence with the current state of the world (for it happens often that objects are not exactly where they were planned to be), and what conditions to monitor during the motion.

The trajectory calculator also is used to provide information to the expander. For instance, it can predict the runtime effects of a given modification of a planned trajectory. This information is useful to the expander for deciding how many different trajectories must be planned for a given motion request, for estimating the feasibility of a given motion, and for other similar purposes.

There are several errors which the trajectory calculator can detect. A request might take the arm outside its range, or force a joint to exceed its velocity limits. It may discover that there is a possibility of collision between the two arms, or between the arm and some object on the table. In order to carry out these tests, it may request assurance from the user that some object lies within a certain region, or it may give the user a warning. The world model is used for much of this calculation. At its discretion, the trajectory calculator may make some critical motions very slow, so that an impending collision will be detected before it happens.

The output of the trajectory calculator is stored in binary files, for loading into the PDP 11.

1.5 USER FEATURES

AL is designed for users of several varieties; not all of the system is of use to each of them. Some users wish to make manipulation programs with primitive motions. Others are interested in combining several often-used library routines in order to make an assembly program. More sophisticated users may wish to create library routines and interact with the intracacies of world modelling. While a task is being executed by the manipulator, a user may wish to monitor its progress, investigate the internal state of the program, or insert patches in the code to fix errors or attempt some modification. Thus, the user may have various degrees of understanding of the AL system, various modes of interaction, and various reasons for using AL.

The bulk of user interaction with AL is during the stage of planning a set of manipulations. This planning has several phases: initial preparation of the program, removing syntactic errors from the source code, trying the program out, and fixing discovered bugs until the program works properly. The final stage is the production run of the program, which can occur in a basically unsupervised mode. During execution, however, it is still possible to interrupt the machine and find out exactly where it is in the plan and debug it further. This is useful for patching a program which over the course of a long execution begins to "drift" from reality.

Thus, the user features can be divided roughly into these parts:

1.5.1 PROGRAM FORMULATION

The AL source language is intended to be a clear and complete system in which to express those manipulations necessary for the correct execution of an assembly task. Writing in AL should be relatively easy; its inherent structure will be great aid in preparing correct programs.

Another way in which AL can assist the programmer is that it can read the current location of an arm and make it available to the programmer. This makes some teaching by showing possible. One way to put together a simple program is merely to move the arm manually to the different locations desired, have the system remember those locations, and then type in appropriate motion commands using these points. In general, a simple "go there" approach fails, because it provides no way to indicate how fast the arm is to move, what forces to apply, what errors to ignore and what conditions to monitor. However, AL will allow one to build complete motion specifications about a skeleton of intermediate points, using textual input to make up for the limitations of purely tactile input.

1.5.2 PROGRAM COMPILATION

The supervisor is the key to this and the following features; it allows the user to oversee the progress of the program and fix errors as they arise. There is a simple *supervisor language* used to communicate with the AL system. Some of its commands are demonstrated in the sample dialog given in Appendix I. One of the commands causes compilation to begin; the parser is directed to read some file. An option is to have console input itself used to enter the source code; this is especially useful in causing the arm to do something immediately. When the parser finds a syntax error, it will give an error message, and several options will in general be available. These include aborting the compilation, skipping to the end of the current statement, editing the line with the system line editor (after which the entire statement will be reparsed, if possible), and temporarily switching to a text editor to fix the problem (after which the entire program must be reparsed).

The compiler detects semantic errors such as generating a move to a point with undefined planning value, not supplying enough information to a high-level primitive, or attempting to move the same arm simultaneously in two blocks of code. In those cases where the problem is one of insufficient information, the expander will prompt for more, and, if possible, continue. The user may decide not to supply that information, and in that case, the offending statement is flushed. Some errors are so drastic that they require complete recompilation; the user is always given the option of switching to a text editor for major modifications.

The trajectory calculator can discover a limited number of errors. These mostly involve motions beyond the capability of the manipulators involved. Options to the user include making the best possible legal trajectory, causing the trajectory to be slowed down, and inserting a trajectory which, when executed, does nothing.

1.5.3 PROGRAM EXECUTION

After a program has been compiled, it resides on disk as a load module. Any number of modules can be loaded together; the principal restriction is that each of them be a "top level" program. As mentioned earlier, the loader will resolve calls between the large (planning) computer and the small (execution) computer for those functions which the user has decided require the computational ability found only on the large computer.

Execution is initiated by a supervisor command issued by the user. While the mini is executing the program, the user can cause an interruption and examine values within the **runtime** system, and modify them if he wishes. It is also possible to examine the code generated by the compiler and modify it, but this is most likely only of interest to system programmers. Sizable patches require recompilation. The programmer (or, at this stage, an operator) can continually examine the status of the **runtime** system by means of the mini's console. Values of variables can be examined and changed, and individual processes can be interrupted without interfering with other concurrent processes.

Sometimes hardware difficulties will cause abrupt termination of the program; these often are due to **runtime** trajectory modifications overstraining the hardware. After issuing an error message to the user, the system behaves just as it would should it have been interrupted manually. It is possible, during one of these "breaks", to request that the entire world be saved. This causes all **runtime** values to be written out into a safe place, along with the current attachment structure and the current program counters. This feature allows the debugging of the task to stop temporarily and to be resumed later. More importantly, it is possible to create a "safe point" in the code, so that if an error should occur later, it is possible to back up the program to a point at which everything was still working.

Programs which have been completely debugged can be "unloaded", that is, saved in a compiled form for execution any time in the future.

CHAPTER2
THE BASIC SOURCE LANGUAGE

AL has several levels of complexity. We will start by discussing the basic source language; this covers enough to write substantial manipulator programs, but has none of the high level capabilities mentioned in the section on goals and philosophy.

2.1 DATA STRUCTURES

2.1.1 DA TA TYPES

In this section we present the data. types available in AL, Roughly speaking, a *data type* is a kind of numeric object. For example, FORTRAN has the data types INTEGER and REAL. A *variable* is an identifier of some type which can take on values. In AL, each variable **must** be ***declared,*** that is, one must state what its type is, somewhere in the program before it is used. There are several reasons for this: It allows the compiler to detect spelling errors, and it allows the same name to be used in different blocks without conflict. AL **uses** ALGOL block structure, which means that all variables declared between a particular BEGIN and END are accessible only to code which appears between the same BEGIN-END pair. The exact details of block structure are discussed in the section on control structures.

2.1.2 ALGEBRAIC DATA TYPES: SCALARS

Algebraic data types are the most familiar. They represent measurements in the real world. An algebraic variable can assume a value by means of the *assignment statement,* which consists of the variable name, a left arrow (**"←"**), and an expression which has the correct type. When **an** assignment statement is executed, the expression on the right hand side is evaluated, and that value replaces the old value of the variable on the left hand side.

The most elementary data type is scalar, which is internally represented as a floating-point number. **Scalars** are used for dimensionless quantities, like **the** number of times **some** operation is to be repeated, or to implement a signal which becomes positive when some critical operation is finished. The arithmetic operations available on scalar variables are addition, subtraction, multiplication, and division; **the** arithmetic operators which perform **these** operations are **the** standard: **+, -, ×, /. As is** usual in algebraic languages, **the** first two have lower precedence than the others.

Scalar constants are written as (base ten) numbers, either with or without a decimal point and fractional part, Here are some examples of declarations and applications of scalar variables:

```
SCALAR sl, s2;
        (Our examples will use a mnemonic scheme for naming variables to clarify the
        type of each entity. Please understand that identifiers can be any string of
        letters, of any length, and that AL does not distinguish between upper and
        lower case. Curly brackets are used in AL to enclose comments.)
sl ← 2;
s2 ← 3.74;
s 1 ← s2 * (s 1 - 3.2);
```

It is often desirable to give some physical meaning to scalar variables. AL provides for scalars with the dimensions *time, distance, angle,* and *mass* in addition to "simple", dimensionless scalars. Time constants are just like simple scalar constants, except they are multiplied by the reserved word *sec* (for "seconds"). The other reserved words related to these dimensioned scalars are CM (centimeters), *deg* (degrees) and *gm* (grams).

Dimensioned scalars are used exactly in the same way as simple scalars; the only difference is that AL will check that addition and subtraction are only performed on compatible values. AL performs dimension checking for each arithmetic operation and each assignment. Addition, subtraction, and assignment require exact dimension match, but if match fails and one of the two arguments is simple (no dimension), it will be converted. Thus it is always legal to use simple scalars where dimensioned ones are expected. Multiplication and division do not require dimension match; they produce a result of a dimension usually different from that of the arguments; this new dimension is then propagated through the expression. In this way, intermediate results can be of dimensions not declared. This causes no problem unless one tries to use such results in an assignment.

Here are some examples of dimensioned scalars:

```
TIME SCALAR tm 1, tm2;
MASS SCALAR msl;
ANGLE SCALAR theta, phi;

tml ← 3 * SEC;
ms 1 ← msl + 2.2 * CM;
msl ← msl + 2.2;
        (The constant 2.2 will be automatically converted to grams.)
theta ← 90 * DEG;
tm 1 ← tm2 * 5.5;
phi ← theta * 4 * DEG;
        {This is a mistake; the right side has dimension angle*angle}
```

If the user feels more comfortable with inches or pounds, it is quite easy to write macros which will make such usage possible. This is best demonstrated by example:

```
DEFINE INCHES = "(2.54 * CM)";
DEFINE FEET = "(12 * INCHES)";
DEFINE LB = "(GM * 1000 / 2.2)";

ms 1 ← 2.2*LB; {= 1 000*GM}
ds 1 ← 3*FEET; {= 3*12*2.54*CM}
```

The user may wish to create new dimensioned scalars, such as forces or velocities. This is readily done by means of the *dimension* statement and a few macros. For instance,

```
DIMENSION FORCE = DISTANCE*MASS/(TIME*TIME);
DEFINE DYNES = "(GM*CM/(SEC*SEC))";
DIMENSION VELOCITY = DISTANCE/TIME;
DEFINE CPS = "(CM/SEC)";

FORCE SCALAR fol;
VELOCITY SCALAR ve 1;
vel ← 2.3*CPS;
fol t vel * 3 * GM / (8.4 * SEC);
```

Please note that the DIMENSION statement and macros follow block structure; it is a good idea co put them in the outermost block.

2.1.3 VECTORS

Scalars are insufficient to describe all measurements of interest to the user of AL. We turn now co ocher algebraic data types. They are syntactically much like scalars: they are declared and can enter into arithmetic expressions and assignments.

The world in which AL resides has three dimensions. We impose a Euclidean structure on that space by setting up three cardinal, orthogonal axes, which meet at the origin. The actual alignment of these *station* axes will, in general, depend on the particular work station involved; it is expected, however, that the positive Z axis will point upwards (this is not at all crucial).

The first data type we will discuss is the *vector.* It represents either a translation or a location. The latter meaning is the result of translating the null vector, that is, the origin of the coordinate system. As is the case with scalars, vectors may be dimensioned.

Vectors can be constructed from three scalar expressions by means of the function VECTOR, The scalar expressions must all be of the same dimension, and the resulting vector has that same dimension.

Addition and subtraction are defined on vectors of the same dimension. One other function is available: the dot product. For example, if the two vectors are:

v 1=VECTOR(x1,y1,z1) and v2=VECTOR(x2,y2,z2),

then we have

```
s * v1 = VECTOR(s*x 1, s*y 1, s*z1)
v1 + v2 = VECTOR(x 1+x2, y1+y2, z1+z2)
v1 - v2 = VECTOR(x1-x2, y1-y2, z1-z2)
v1 . v2 = x1*x2 + y 1*y2 + z1*z2
```

Thus, addition and subtraction produce vectors in the familiar way; the dot product is the sum of the products of the three components; its dimension is the product of the dimensions of the two arguments.

It is possible co "stretch" or "shrink" vectors by multiplying and dividing them by scalars. The dimension of the resulting vector is the product or the quotient of the dimensions of the two arguments. The magnitude of a vector is calculated by the function ABS, which returns a scalar of appropriate dimension.

There are several predeclared vectors in AL:

```
VECTOR X, Y, Z, NILVEC;
        (There are predeclared and have values as follows)
X t VECTOR(1,0,0);
Y t VECTOR(0,1,0);
Z t VECTOR(O,O,l);
NILVEC ← VECTOR(0,0,0);
```

The components of a vector can be easily extracted as the dot product of the vector with X, Y, or Z. Here are examples of other vectors:

```
VECTOR v 1;
DISTANCE VECTOR dv 1, dv2;
SCALAR sl;
DISTANCE SCALAR dsl, ds2;

dsl ← 4 * CM;
sl ← -2;
dv 1 ← VECTOR(s1, 2.3, ds1);
        (This is a distance vector; the simple scalars get converted.)
ds2 ← dv 1 . Y; (So ds2 gets 2.3*CM }
v 1 ← dv 1 / ds2; (So v1 ← VECTOR(-2/2.3, 1, 4/2.3).}
dv2 t ds2 * v 1; {So v2 ← dv1}
s 1 ← ABS(v 1);
```

2.1.4 ROTATIONS

The *rot*, our next data type, represents either a rotation or an orientation. The latter is the result of applying the rotation co the station coordinate system. Rots are internally stored as *3x3* matrices, which operate on column vectors in the usual way. Thus rots can operate on vectors and move them around the origin (without changing their length); they can also operate on other rots (by matrix multiplication). To rotate a vector (about the station origin), multiply the vector (on the right) by the rot (on the left). To compose rots, multiply them together; the one on the right will be applied first.

A rotation can be constructed with the function ROT, which takes two arguments: a simple vector, which is co be the axis of rotation, and an angle, which is the amount Co rotate. The direction of rotation follows the right-hand rule; a rotation of 90 degrees about the X axis moves the Y axis into the Z axis. This turns out Co be a general representation far easier Co write and understand than raw matrices. We hope the following examples will serve Co clarify the proper use of rots:

```
ROT r 1, r2, r3;
ANGLE SCALAR alpha, beta, gamma;
rl t ROT(X, 90*DEG);
v1tr1 ::: Z;
        (VI gets Z rotated 90 degrees about X, so VJ ← VECTOR(0,-1,0).}
r2 ← ROT(Y, 45*DEG);
r3 ← r2 * rl;
        (Thus, r3 means: rotate first 90 degrees about the X axis, then 45 about the
        original Y axis.}

r 1 ← ROT(X,alpha);
r2 ← ROT(r1*Y,beta);
r3 t ROT(r2*Z,gamma);
r4 ← r3 * r2 * r 1;
        {r4 is then a rotation with this meaning: Rotate by alpha degrees about the X
        axis, then by beta degrees about the new Y axis, then by gamma degrees about
        the doubly new Z axis.}
```

The null rot, which has no effect,-is called **NILROT**.

2.1.5 FRAMES

The next data type is the *frame,* used co represent a coordinate system. It has two components: the location of the origin (a distance vector) and the orientation of the axes (a rot). Frames are typically used to describe objects; one can specify locations of features on an object by translating them from the object's origin.

There are several predeclared frames in AL. *Station* is the frame which represents the work station's frame of reference. Each hand available to the system also has a frame variable, whose value (continually updated) is the position of that hand. Currently, there are two such frames: *yellow* and *blue.* Each arm has a rest, or park position, known as *ypark* and *bpark*.

A frame may be constructed by a call on the function FRAME:

```
FRAME fl;
DISTANCE VECTOR dv1;
ROT rl;
.
f1 ← FRAME(r1,dv1);
```

The two arguments are a a rot (for the orientation) and a distance vector (for the position). To extract the rot or the vector from a frame, use the functions ORIENT and LOC, respectively. To find where a vector goes if its base is moved from the station to the coordinate system of some frame, "multiply" the frame (on the left) by the vector (on the right). To translate a frame by some distance, simply add a distance vector to it.

Often one wants co construct a vector which is oriented like some vector (for example, the X vector) in some frame, say F1. The *with respect to* operator *WRT* gives exactly that; one writes (X WRT F1). Examples of this and other constructs pertaining to frames follow:

```
FRAME f1, f2;
f 1 t FRAME(ROT(Z,90*DEG),2*X);
        {f1 sits 2 centimeters from the station, in the X direction. Its coordinate system
        has X where the station's Y points.)
v1 t X WRT f 1; (This evaluates to VECTOR (0,1,0).}
f2 t f 1 + v 1; {Just like f1, but with origin at (2,1,0).}
v 1 ← f1 * Y; (This evaluates to VECTOR (1,0,0)}
v2 ← v3 WRT f2;
        (This is equivalent to (f2*v3) - LOC(f2), and also to OR IENT(f2)*v3.}
```

2.1.6 PLANE S

Next we have the *plane,* used to separate space into regions and Co specify the locus of searches. Planes are formed by use of the function PLANE, which takes two distance vectors as arguments: The plane is co pass through the first vector, and the outward-facing normal to the plane is in the direction of the second vector. Thus PLANE(X,Y) is a plane parallel to the X-Z plane, translated from it by one centimeter in the X direction.

Planes are internally stored by four numbers: the first three are an outward-facing normal, and the last is the opposite of the distance from the plane to the origin.

Each plane divides space into three regions: inside, on, and outside the plane. (The last set contains all points on the same side as outward-facing normal.) To find out in which region a point (represented by a distance vector) lies, extract the inner product of the vector with the plane. Its value is a distance scalar whose absolute value is the shortest distance from the vector co the plane, and whose sign is negative if the vector is inside the plane, 0 if the vector is on the plane, and positive if the vector is outside the plane. The arithmetic operator for the inner product is a

dot; the plane may appear on either side of the dot. If the plane P has an internal representation consisting of four numbers A, B, C, and D, and V = VECTOR(X1,Y1,Z1), then we have:

```
P . V = A*X1 + B*X2 * C*X3 + D
```

Other operations available on planes are translation (by adding a distance vector) and rotation (by multiplying by a rotation). To get the outward-facing normal of a plane, use the function NORMAL, which takes a plane argument and returns a distance vector.

Examples:

```
PLANE p1, p2;
p1 t PLANE(VECTOR(0,0,0),Z);
        (This is the surface of the station)
v1 ← NORMAL(p1 + v2);
        (No matter what v2 is, v1 will get Z)
ds1 ← p1 . VECTOR(2, -13.2, 32.3);
        {ds1 gets 32.3*cm}
```

2.1.7 TRANSFORMS

The last of the algebraic data types is the *trans,* which stands for "transform". It is an operator, Chat is, a function, which can operate on vectors, frames, and planes. The application of a trans Co any of these is written as if it were a multiplication, with the trans on the left. To compose several transes together, "multiply" them, with the one co be applied first on the right.

The trans itself is defined as a function which can take objects in one frame of reference into another. One can construct a trans by use of the function TRANS:

```
TRANS c1;
VECTOR v1;
ROT r1;
.
c1 ← TRANS(r1,v1);
```

The two arguments are a rotation the rotational part and a vector (the translational part). The application of a trans to a vector, frame, or plane first rotates that object according to the rotation part (rotating about the station origin), and then translates the result according Co the translational part.

Transes, like vectors and scalars, carry dimension. The rule is that when a trans is applied to a vector, they must agree in dimension; the resulting vector is of the same dimension. When a trans is applied co a frame, it must be a distance trans. When a frame is used in a context demanding a transformation, it will be understood as a shorthand for the distance trans leading from the station. When transes are composed, they must agree in dimension.

There is another convenient way to specify a trans: by forming it from two frames. The trans is then the function which takes the origin of the first frame across to the origin of the second, performing a rotation first to get the axes aligned. This method of specifying a trans is accomplished by use of the arithmetic operator "→".

Examples:

```
TRANS t1, t2;
t1 ← f1 → f2; {Thus t1*f1 = f2}
v1 ← t1 * v2;
t2 ← t1 * t1;
v1 ← f1 * v2; (Equivalent to (STATION→f1)*v2}
```

The null trans, equivalent to TRANS(NILROT,NILVEC) is called NILTRANS.

2.1.8 PLANNING VALUES

AL works under the fundamental philosophy that arm motions should be planned in advance. Since an arm trajectory cannot be calculated reasonably unless the end-points (and any specified intermediate points) are known fairly accurately, it is necessary that the compiler maintain for each variable a *planning value* which may be used in the case that the variable enters into a motion specification. Planning values are discussed in more detail in Section 3.2.

Essentially, the compiler attempts to assign to each variable a planning value for each statement in the program. Initially, the planning value of each variable is "undefined"; one of the ways that a planning value can be assumed is through an assignment statement. The compiler evaluates the planning value of the right hand side, and this becomes the new planning value of the variable on the left. Propagating the planning value across loops is complicated; in the case that the variable can take multiple values, the compiler either sets the planning value to "undefined" or, as AL becomes more advanced, maintains parallel "worlds" in which each planning value is monovalued.

Variables can attain different values at run-time than their planning values when some real-world measurement is taken and the result used in an arithmetic expression. The most common example of this is that the frames *yellow* and *blue* are always kept accurate at run-time by feedback from the arm hardware, so their values will in general differ from those planned.

2.1.9 ARITHMETIC

Here is a summary of the arithmetic expressions available. They are grouped by the type of their values. These abbreviations are used: 's' = scalar, 'v' = vector, 'r' = rot, 'f' = frame, 'p' = plane, 't' = trans.

scalar expressions:

s + s	scalar addition (commutative)
s - s	scalar subtraction
s * s	scalar multiplication (commutative)
s / s	scalar division
v . v	dot product of two vectors (commutative)
P . v	signed distance from vector to plane (see discussion above on planes)
v . P	signed distance from vector to plane (see discussion above on planes)

vector expressions:

s * v	dilation of a vector
v / s	contraction of a vector
v + v	vector addition (translation of the first vector by the second) (commutative)
v - v	vector subtraction
r * v	rotation of a vector
t * v	transformation of a vector
v WRT f	a vector of length ABS(v) rotated into f's system; like ORIENT(f)*v; that is, a vector in station coordinates which looks to the station as v does to f.

rot expressions:

r * r	composition of two rots (first to be applied is on the right)

frame expressions:

f + v	translation of a frame
t * f	transformation of a frame

plane expressions:

P + v	translation of a plane by a vector
r * p	rotation of plane (about station origin)
t * p	transformation of a plane by a trans

trans expressions:

f → f	transformation which leads from the first frame to the second
t * t	composing two transes. The one on the right will operate first.

PREDECLARED CONSTANTS AND VARIABLES:

π is simple, has value = 3.14159...
STATION is a frame which has standard station coordinates. (constant)
BLUE is the location of the blue hand.
YELLOW is the location of the yellow hand.
BPARK is where the blue hand parks. (constant)
YPARK is where the yellow hand parks. (constant)
X is **VECTOR(1,0,0)**.
Y is **VECTOR(0,1,0)**.
Z is **VECTOR(0,0,1)**.
NILVEC is **VECTOR(0,0,0)**.
NILROT is **ROT(X,0*DEG)**.
NILTRANS is **TRANS(NILROT,NILVEC)**.

EXTRACTION FUNCTIONS:

LOC(FRAME) is a vector whose value is the location of the frame.
ORIENT(FRAME) is a rot whose value is the orientation of the frame.
NORMAL(PLANE) is the outward facing normal vector of a plane.

2.1.10 SOME EXAMPLES OF ARITHMETIC EXPRESSIONS

In the following examples, assume these declarations:
FRAME f1, f2, etc;
VECTOR vl, v2, etc;
SIMPLE sl, s2, etc;
ROT rl, r2, etc;
PLANE pl, p2, etc;

f1's unit Y vector, in station coordinates:
```
f1 * Y
```

f l's Z vector as seen from f2:
```
(f2 → f 1) * Z
```

A vector pointing in same direction as f l's X coordinate:
```
X WRT fl
```

v 1 rotated 90 degrees about the station's Z axis:
```
ROT(Z,90*DEG)*v 1
```

fl's Y-Z plane:
```
PLANE(LOC(f 1),X WRT f 1)
```

A plane 3 centimeters above the station:

```
PLANE(VECTOR(0,0,3),Z);
PLANE(3*Z,Z);
```

An identity with WRT:

```
v1 WRT f1 = ORIENT(f1)*v1 = (f1*v1) - LOC(f1)
```

2.2 MOTIONS

Motion statements are at the heart of AL; it is by them that all manipulatory work is done.

2.2.1 COMPILE-TIME AND RUNTIME CONSIDERATIONS

All motion statements cause the compiler to make some plans which will eventually be executed. Those motions which depend on the value of some frame expressions for intermediate and final position will be planned using the compile-time planning values for all relevant expressions. This can lead to inaccurate plans, since at runtime, some of those expressions might have different values. An example is an expression involving the location of the arm; the variables *yellow* and *blue* are always kept accurate at runtime by reading the arm locations. Since every arm motion must begin at the current arm position, this is an implicit parameter to the motion specification which may not agree with its planning value. This is a special case of a general phenomenon: objects are seldom exactly where they were planned to be, and the runtime value of their frames will very likely be based on the position of the hand after it successfully locates the object by sensory feedback.

Thus it becomes necessary that the runtime system adjust all trajectories immediately before they are executed. Adjusting a trajectory is less time-consuming than the original calculation; it makes sense to adjust before each repetition of a motion, whereas it would be a waste of computer time to recalculate trajectories that often. Immediately before the arm starts moving on a trajectory, then, the plan is modified to bring it into line with current values of frames. If there is any discrepancy between the runtime and compile-time understanding of where any frame is, the servo will try to place the arm in the right place nonetheless.

There are limits to the proper use of this feature; if the planning value is seriously in error (which can happen if the error is but a few centimeters, depending on the arm being used and its configuration), then the attempt to make last-minute corrections might overstrain the arm or impair response to directional forces. It is the user's responsibility to foresee large discrepancies in the planning value and to program in a condition to select one of several possible moves. Hopefully, this will be seldom needed.

After a motion has been completed, the new location of the hands will be read, and that will

determine the new value for *yellow* and blue, as well as for any frames which might be affixed to them. For the moment, we will ignore affixments; they are discussed in great detail later.

2.2.2 SIMPLE MOVES

In this section we will discuss motions which are to be executed on only one arm. Let us start with an example:

```
FR AM E frobgrasp, swing l, swing2;

'MOVE yellow
      TO frobgrasp
      VIA swingl, swing2
```

This example demonstrates the general syntax; the reserved word MOVE is followed by the name of the arm to be moved and a set of clauses, each beginning with a reserved word (here the words TO and VIA). There is no punctuation necessary at the end of a clause. The arm is expected to travel from its current position (wherever that is planned to be) to the final position (*frobgrasp*), passing through the intermediate positions (*swingl* and *swing2*). A smooth trajectory for the motion will be computed by splining together polynomial segments (usually third degree, occasionally fourth) separately for each arm joint. This trajectory calculation is somewhat time-consuming and is done completely at compile time.

Certain things must be specified for any move. First is the arm which is to be moved. It is named by an arm frame (*yellow* or *blue*); other ways of specifying the arm will be mentioned after the formal idea of affixment has been presented. Next, the destination frame must be specified. "TO *frobgrasp*" means that at the end of the motion, the position of the arm should coincide with the position of *frobgrasp*. There is a notational convenience for destinations: They can be specified in terms of where the arm is at the start of the motion. The symbol for this is "⊗" (sometimes pronounced "grinch"), that is, ⊗ is a frame which has the location and orientation of the arm at the start of the motion. Thus,

```
MOVE yellow TO ⊗ + Z:CM
```

will move the arm 1 centimeter in Z above its starting place.

2.2.3 CONDITION MONITORS

During the course of an arm motion, it may be desired to monitor some condition or set of conditions in order to prematurely stop the motion or inform some parallel process that a condition has occurred. The conditions which may be checked are results of measurements, such as time or force checking, and *events,* which are signals that can be explicitly sent by other simultaneous processes. Events will be discussed in subsection 2.5.4; for the time being, assume that the only conditions which may be checked are measurement conditions. Here is an example which contains some *condition monitors:*

```
SCALAR warning;
VECTOR v1;

MOVE yellow
        TO ypark
        ON DURATION ≥ 3*SEC DO warning ← 1
        ON FORCE(v1) ≥ 18*OZ DO STOP (Stops the arm)
```

This motion has two separate and independent condition monitors; the first will trigger if the motion takes longer than three seconds, and the second will trigger if the force on the hand, as measured along vector *v1*, exceeds 18 ounces. (Assume we have a macro which translates ounces into units of force.) The *conclusion* of a condition monitor, the code which will be executed if the monitor triggers, is one statement prefaced with the reserved word DO.

A condition monitor has two states: *enabled* and *disabled.* Generally, a condition monitor will be enabled as soon as its motion statement is started, and it becomes disabled when the motion ends. As soon as a condition monitor triggers, it becomes disabled unless it becomes explicitly reenabled. Reenabling is done by executing the statement ENABLE 'within the conclusion.

In order to enable or disable some arbitrary monitor, it is necessary to give it a name; this is done by putting a *label* immediately before the word ON. A label is an undeclared identifier followed by a colon. Thus we could write:

```
MOVE blue TO frobgrasp
        test 1: ON DURATION ≥ 3*SEC DO DISABLE test2
        test2: ON TEMPERATURE < 30 DO STOP
```

Thus, test2 is only performed for the first three seconds.

Occasionally one wants to write a condition monitor which is initially disabled and becomes enabled later. This is accomplished by putting the word DEFER before ON:

```
fudge: ON temperature > 400 DO
        BEGIN (Keep shouting until someone hears.)
        WRITE("BURNING");
        STOP OVEN; (Pretend we have a device OVEN)
        EN ABLE (This reenables fudge}
        END
taste: DEFER ON cooked {This is an event.} DO DISABLE fudge
ON DURATION > 30*MIN DO ENABLE taste
```

It should be noted that this ability to enable and disable monitors explicitly is a non-structured construct; using it can lead to unintelligible programs. In any case, scope rules must be observed; it is not legal to enable or disable monitors across different MOVE statements. This means that two motion statements which happen to be simultaneously executing (we shall see how to do this later, in subsection 2.5.2) cannot interfere with each other's condition monitors,

Boolean combinations of conditions are not allowed. Some of the continually measured functions

which may be tested are force along a vector, (FORCE(V)), force about an axis (TORQUE(V)), time since beginning of motion (DURATION), and the force between the fingers (SQUEEZE). One standard event is testable: ARRIVAL. This event occurs when the motion terminates due to having reached its destination. It does *not* become true if the arm stops for reasons other than normal arrival at the destination; STOP does not trigger it.

The conclusion of a condition monitor may be any statement, including an entire block. The only restriction is that if a motion statement is the only statement in the conclusion, it must be surrounded by BEGIN and END. (This is necessary at times to prevent ambiguity.) The compiler will complain if you try to embed a motion statement inside another if the result implies simultaneous motion statements for the same device.

The existence of condition monitors raises this question: When is the motion really finished? It can happen that the arm itself has stopped, but some monitor has triggered, and its conclusion is still busy being executed. The rule is this: the motion is declared done when all the joints of the arm are stopped, and all monitors are either disabled or not currently triggered. Any monitors still enabled, but not triggered, are disabled at the time that the motion is declared finished.

The user must be aware of some timing considerations. Firstly, measurements like FORCE, DURATION, and SQUEEZE are not really computed continually; there is a process which makes a measurement and then lies dormant for a while (on the order of twenty milliseconds) before again making a measurement. Thus, monitors do not trigger immediately when a tested condition becomes true. Secondly, when a monitor triggers, any initial statements of enabling or disabling are done immediately, but any arithmetic is scheduled to be done at some point in the near future. Therefore it is not possible to guarantee that a critical computation happen immediately. If the user desires, he may use the word CRITICAL at the start of the conclusion, and UNCRITICAL at the start of that code which need not be guaranteed immediate execution. Only one occurrence of CRITICAL, at the very start of the conclusion, and only one occurrence of UNCRITICAL are allowed. AL automatically assumes CRITICAL before initial statements of enabling and disabling, and UNCRITICAL immediately following. An example:

```
ON DURATION ≥ 4*SEC DO          (Tested frequently}
    BEGIN
    ENABLE goodguy;             {Assumed CRITICAL)
    t ← 3;                      {Assumed UNCRITICAL)
    END
ON SQUEEZE ≥10*OZ DO            (Tested frequently}
    BEGIN
    CRITICAL;                   (Overrides defaults}
    t ← 4;                      {Will be done immediately)
    UNCRITICAL;                 {End of critical region)
    DISABLE goodguy;            {Done soon)
    END
```

2.2.4 FORCE DURING A MOTION

To make the arm compliant to external forces along some directions or about some axis it is necessary to specify the appropriate modes of freedom. Because AL works in three-dimensional space, it only makes sense to specify at most three orthogonal directions and three orthogonal axes. In addition to being compliant along degrees of freedom (whether translational or rotational), it is also useful to apply a fixed force along some of these degrees. Then pure freedom reduces to application of zero force.

For example, suppose the arm is on the surface of the station; we wish to apply a force of 10000 dynes directly downward (the negative Z direction) while allowing the arm to comply to any horizontal force. This is how we would write such a motion:

```
MOVE blue TO ⊗ (moues nowhere)
    WITH DURATION =10*SEC {give it some tine.)
    WITH FORCE =-10000*DY NES ALONG Z OF station
    WITH FORCE = 0 ALONG X, Y OF station
```

This example illustrates several conventions. A translational degree of force (or freedom, if the amount of force is zero) is specified by the word ALONG followed by a list which can only contain the vectors X, Y, and Z, followed by the word OF and the name of the frame which specifies the coordinate system in which the cardinal axes are to be understood. The amount of force must be in force units, which are of the scalar dimension *mass*distance/(time*time)*; we have assumed in the example above that DYNES is a macro which expands to correct units.

Rotational degrees of force are written in much the same way; the axes are specified ABOUT a combination of X, Y, and Z OF some frame, like this:

```
WITH FORCE = 5000:::DYNES ABOUT Z OF ⊗
        {Applies a torque about the Z direction of the hand.)
```

During a motion which has only translational force specifications, the orientation of the hand will remain as planned, but the location will comply with the specified force. During a motion which has rotational degrees of force, the orientation of the hand will vary from that planned in accord with the specification and whatever external forces are encountered.

It does not really make sense to have a force in the nominal direction of motion, but there is neither a compile-time nor a runtime check to catch such usage. If it happens, the arm could go into oscillation.

Actually, not all of the full power of force specifications will be available in the first versions of AL. In particular, rotational specifications will be handled roughly or not at all. Another future embellishment will be to allow the directions of force to vary during the motion; this is useful for such tasks as turning a crank. For example, the following will eventually be available:

```
MOVE yellow TO frobgrasp
    WITH FORCE = SIN(DURATION*DEG)*10000*DYNES
        ALONG Z OF ⊗;
```

This specifies a varying amount of force along a varying direction: "⊙" means "the *current* location of the hand, as it changes during the motion."

Especially at first, some of the force control will be prepared by the compiler, not calculated during the arm motion itself. Therefore, if the **runtime** values of the endpoints of motion are significantly at odds with their planning values, application of force may go awry.

2.2.5 DE PR OACHES

Many objects have shapes which necessitate care as the arm approaches them or departs from **them**. AL supplies a method for insuring that every time the arm approaches a frame, it will pass through an associated spot first, and every time it leaves that frame, it passes once again through the same spot. The "spot" is termed a ***deproach*** (from departure and **ap*proach***); it is a transformation to be applied to the frame involved in order to discover the appropriate place through which to pass. The fact that a trans is used implies that the deproach point will move about with its frame. It also means that the location of the deproach point is relative not to the origin of the frame, but rather to the point in frame coordinates to which the motion leads. For example, the deproach transformation of the station is **TRANS(VECTOR(0,0, I 0*CM),NILROT)**. If the arm is to go to, say, the point **VECTOR(3,1,4)*station** using station's deproach, then it will first go through **VECTOR(3,1,14)**. This has the effect of preventing the arm from going through the surface of the station.

The deproach of a frame is specified by means of an assertion. Without going into full detail on assertions (which will be covered in detail in Section **3.4**), we give some examples:

```
ASSERT FORM(DEPROACH, station, TRANS(NILROT,VECTOR(0,0,10*CM));
        (This is preasserted and need never be included.)
ASSERT FORM(DEPROACH, frob, TRANS(ROT(X,90*DEG),VECTOR(1,0,0)));
        (Whenever you go to frob, go through a point 90 degrees about frob's X axis
        from a spot one centimeter in X from the nominal arrival point.)
```

Note that since **deproaches** are transformations, they have the power to include rotations. These are considered to be rotations about the origin of the coordinate system involved; the rotation occurs, as usual, before translation. The use **of** rotations is of marginal use, but is included for completeness.

The deproach points of the departure frame and the arrival frame are used as implicit VIA points for any motion, except when the destination is "⊗" or there is an overriding deproach clause-in the motion statement. Here are some examples:

```
MOVE yellow TO ⊗; (No departure or approach point used)

MOVE yellow TO frob
    WITH APPROACH = NILDEPROACH;
        {The default departure (which depends on the last motion made by
        yellow) is used, but no approach point is desired.)

MOVE blue TO frob
    WITH DEPARTURE = NILDEPROACH
    WITH APPROACH = DEPROACH(frobgrasp);
        (No departure point is desired, but the approach should be as if the
        destination were frobgrasp, not frob.}
```

Suppose that a frame f is given deproach transformation d. It is desired to find the frame which is the deproach point from some other frame h (for example, where the hand is, for departure), using f's deproach. The frame which will be used as a via point is this:

```
f * d * (f → station) * h
```

The deproach point for f itself is discovered by setting h = f in the above expression. The identities

```
(f → station) * f = station, and a * station = a
```

reduce the resulting expression to f * d; this is therefore f's own deproach point.

We have not yet discussed affixment of frames, but the actual decision of which deproach to use in a given situation depends on it somewhat, so let us just mention that there is a way to specify that two frames are affixed, so that whenever on moves, so does the other. Exact details are given in Section 2.3. With this understanding, we can describe the method used to describe how AL determines what deproach to use:

When an arm moves *to* a frame, t-he frame's own deproach is used, if it has one. If not, then a search is made along the string of affixments (that is, frames to which the given frame is affixed are searched) until one is found which has a deproach. That deproach is the one that is used. If none at all is found, then the station's deproach is used as a default. (One way to think of this is to consider all frames ultimately affixed to the station.) In approaching a frame which is the result of a calculation, as in

```
MOVE yellow TO frob + VECTOR(0,0,1)
```

the default approach is NILDEPROACH. The default deproach of ⊗ is also null.

In departing *from* a frame, it matters whether or not that frame is now attached to the hand. If not, then the same algorithm used for finding departure is used for approach. But if the frame has been detached from some erstwhile mother and is now attached to the hand, then its old

mother's deproach is used (and if there is none, the same search is made). Thus, a frame attached to the hand still has some "memory" of its previous state of attachment.

2.2.6 OTHER MOTION CLA USES

Here we describe some of the other additional clauses that may be associated with **motion** statements. The first is WITH DURATION, which allows the user to specify the timing for the motion. One can use ≥, =, or ≤ for duration control. The first is used to guarantee that the motion take a certain amount of time, that is, it guarantees that the motion will be slow enough so that all the time is used. The second is rarer; it is used when the exact time is somehow critical. If the compiler thinks that the arm cannot move fast enough, it will complain. The third form is included primarily for completeness; once again, it can cause the compiler to complain. In the absence of any timing specification, AL will compute the least time which will allow the particular arm being used to move most efficiently.

VIA is used to name desired points along the trajectory. In its simplest form, the VIA clause contains merely a list of frame expressions, such as in this example:

```
MOVE yellow TO finalpoint
    VIA intl, int2 + VECTOR(0,0,1), int3;
```

The motion will be planned to go from the current location of the yellow arm, through a departure point (if there is one), through each of the intermediate frames, through the approach point (again, if there is one), and finally to arrive at finalpoint.

At each of the intermediate points, it is possible to specify the velocity to be achieved at that point (in terms of a velocity vector) as well as upper or lower bounds on the time used to reach this frame from the previous one on the list. Here is an example demonstrating these features:

```
MOVE blue TO finalpoint
    VIA intl WHERE VELOCITY = velol, DURATION = 3*SEC
    VIA int2 WHERE DURATION ≥ 7*SEC
    WITH DURATION ≥ 10*SEC;
```

This specifies two intermediate points, each of which has some condition associated with it, A time constraint for the entire motion is also given. Note that the word VIA must be repeated when conditions are specified for some Intermediate point.

One final feature is available with respect to intermediate points: One may specify that a piece of code is- to be initiated when any intermediate point is achieved. This is done with a THEN construct:

```
MOVE red TO rpark
    VIA intl THEN WRITE("Almost there!")
    VIA int2 THEN ENABLE prepare-for-landing;
```

The statement following THEN may not be a motion statement for the same arm; if the statement is a motion statement, it must be surrounded by BEGIN and END. It is legal to have combinations of velocity, duration, and THEN-type specifications all at the same intermediate point.

DIRECTLY is a clause that tells the compiler that only the via points and the final point are of interest; no smooth trajectory need be planned. A smooth motion will result due to runtime calculations. This will also set the deproaches to NILDEPROACH.

TRACING is another option. It allows the user greater control over, the exact trajectory chosen for the move. The path can be traced at whatever speed desired. The path, or *parameterized frame,* is a specification of what frame the arm is to go through for each value of the parameter. It is also possible to specify the relation between the parameter and real time, as well as the state the grain of the motion (that is, how often the actual location should coincide exactly with the parameterized frame) or the acceptable tolerance (by a distance scalar). A glorious and complete example:

```
ANGLE SCALAR alpha;
FR AM E cen ter;

MOVE yellow (No destination specified with a tracing motion.)
     TRACING center + 12*VECTOR(COS(alpha),SIN(alpha),0)
     FOR alpha ← 0 BY 10*DEG UNTIL 360*DEG
     WITHIN .1*CM (This is the tolerance.)
     WITH DURATION =10*SEC;
```

This specifies a circular motion of radius twelve centimeters parallel to the surface of the station, about the frame *center.* Every 10 degrees, the arm should actually be in the right place, and, furthermore, it should never be more than .1 centimeter (pretty tight tolerance, actually; most likely beyond the capability of the manipulator) from the perfect circle.

The option MAINTAINING ORIENTATION causes the trajectory computed by AL to try to maintain the same hand orientation throughout the motion. Of course, the final orientation **must** be the same as the initial orientation for this to work at all.

2.2.7 COMPLEX MOVES

A complex move is one which involves more than one arm at a time. A distinction can be made between moves which merely require simultaneous acquisition of "agreement points" (let us call this- weak synchrony), and those which require true coordinated motion throughout (strong synchrony).

Weak synchrony is achieved by pairing frames to make composite VIA points and destinations. A paired frame has the form: [F1 : F2]. Here is an example of a move statement using paired frames:

```
FRAME yl, y2, y3, y4, b1, b2, b3;
.
MOVE [yellow : blue]
      VIA [y1:b1],[y2:],[y3:b2]
      TO [y4:b3]
      ON [FORCE(Z)>3000*DYNES:] DO STOP
```

The via list is composed of a set of paired frames, where an empty field indicates "don't care", In the example shown, the arms start together, achieve y1 and b1 simultaneously, the yellow arm passes through y2, and together they pass through y3 and b2.

It is now more cumbersome to specify condition monitors and conditions in general, The paired construct applies for all the optional fields; thus, one can write

```
WITH FORCE = [14000*DYNES:] ALONG [X OF yellow:]
```

The meanings of ⊗ and ⊙ are now relative to which side of the pair they occupy; in the example above, the left side always refers to the yellow arm, and the right side to the blue. To override this convention, one may use expressions like "⊙.yellow", or "⊗.blue".

The meaning of STOP in the example above is extended to both arms at once; in order to specify only one, it is necessary to say "STOP yellow" or "STOP blue".

Strong synchrony involves one concept not included above: The ability to specify the location of one arm throughout the motion in terms of the location of the other arm. The construct which allows this specification is COORDINATING; it allows one to give an expression for the location of one of the two arms. Suppose we wish to keep both arms in "lockstep", that is, the blue arm should retain its relative position to the yellow arm throughout the motion. (This might be necessary for lifting some object by its two ends.) One way to code this task is as follows:

```
FRAME y1, yint1, yint2;
MOVE [yellow : blue]
      TO [y1:]
      VIA [yint1:],[yint2:]
      COORDINATING LOC(blue) = LOC(yellow) + ⊗.blue - ⊗.yellow
      WITH FORCE = [:0] ALONG [: X,Y OF blue]
      [MAINTAINING ORIENT : MAINTAINING ORIENT]
```

2.2.8 SEARCHES

A SEARCH is very much like a move. It is a means of specifying repeated action in a spiral. As with a MOVE, it is necessary to name a controllable frame which is to be moved. The ON construct is exactly as for MOVEs.

Here is a complete example of a search:

```
PLANE pl;

SEARCH yellow
        ACROSS pl
        WITH INCREMENT = 3*CM
        REPEATING
                BEGIN (This is done at each iteration)
                FRAME set;
                set ← yellow;
                MOVE yellow TO ⊗ - Z
                        ON FORCE(Z) > 3000*DYNES DO TERMINATE;
                MOVE yellow TO set DIRECTLY;
                END
```

The plane of the search is specified by the ACROSS construct. A spiral box search will be performed in this plane (or parallel to it, it the initial location of the hand is not in the plane); the increment for the search will be three centimeters. At each point in the search, the statement following REPEATING is executed; in this case, that involves two motions. The special statement TERM INATE causes the search to finally succeed; if there is an ON ARRIVAL clause in the search, it will trigger when TERMINATE is executed. It is also possible to terminate a search by setting some flag inside the repeated code, and to test it in a condition monitor associated with the search, That monitor can execute the statement STOP, causing the search to be halted, In this case, any test for ARRIVAL will never trigger.

2.2.9 CENTER

Occasionally the hand is positioned around an object, but it is not certain if it is centered. One wants to close the fingers slowly, moving the arm meanwhile to accomodate to the location of the object. This is accomplished by means of the CENTER command. The direction that the hand will move is the direction between its fingers. All that the CENTER command needs is the name of the arm being moved. The use of ON is the same as for a search or any other motion.

Here is a simple example:

```
CENTER blue
        ON SQUEEZE > 4 DO STOP
```

Note that this is command, unlike MOVE, treats the fingers and the arm together as one device.

2.2.10 CONSTANT VELOCITY M OTION

A special form of the MOVE instruction is provided to cause the arm to quickly achieve a particular velocity and to hold it in straight-line motion for a given distance:

```
VELOCITY VECTOR vv 1;
VECTOR v 1;
FRAME dest;

MOVE yellow
        WITH VELOCITY = vvl
                THROUGH dest
                FOR DISTANCE = 4*CM
        ON FORCE(v I) > 2000*DYNES DO STOP
```

The VELOCITY clause tells which vector to follow, and how fast. The THROUGH clause tells the compiler where the move expects to end. The FOR DISTANCE tells the maximum distance the hand should go. It is general practice to terminate such a move by use of a condition monitor.

2.2.11 STOPPING

Generally, an arm will stop its motion when it has achieved its destination. Often it is necessary to stop it prematurely, for example, if some error condition is detected. The statement

```
STOP yellow
```

causes the yellow arm to be unconditionally stopped; any motion statement operating it will terminate. This statement may be executed at any point in the program, not just inside a motion statement.

2.2.12 *DE VICE CONTROL*

Each device has a name; currently, the legal device names are *yellow,* blue, vice, *driver* (an electric screwdriver), *yfingers, bfingers* (The fingers of the two arms). STOP without any device name is only legal within a motion command; it stops whatever device(s) that command is operating. STOP followed by a device name will unconditionally stop that device.

There is a general command for operating devices other than arms; it is hoped that this will be flexible enough for any device we are likely to use (if not, we will add special new forms). Assume we have the device *turntable,* which is capable of moving at any velocity and for any length of time, but which cannot go to a particular set point. Then the syntax would be this:

```
OPERATE turntable
        WITH VELOCITY = 3*DEG/SEC
        WITH DURATION = 8*SEC
```

The idea is that the WITH construct will suffice to account for any special data (in this case, velocity and duration) peculiar to the particular device. The OPERATE statement also allows the ON construct, so it can test for special conditions and take appropriate actions; it also always allows WITH DURATION.

The screwdriver is a hand-held device which can be run at a range of speeds, in either direction. By convention, a positive velocity means clockwise, and a negative velocity means anticlockwise. The relevant reserved word is VELOCITY, which is equated with the name of a scalar variable of dimension *angle/time*. This variable will be queried periodically during the screwdriver motion to determine how much voltage to apply to the motor. This allows the velocity to change during the operation of the device, perhaps under the control of a parallel process which is monitoring some conditions. An example:

```
OPERATE driver
    WITH VELOCITY = sp
    WITH DURATION = 4*SEC
    ON DURATION>2*SEC DO sp ← 2*sp
        {After two seconds, speed up the screwdriver.}
```

Each arm has two fingers at the end which are capable of closing and opening at various speeds. The relevant reserved words are OPENING, which is to be set to the desired (distance scalar) opening, and VELOCITY, which is to be set to the (velocity scalar) speed desired. It is possible to refer to the force scalar variable SQUEEZE, which indicates the force being applied by the fingers. Condition monitors can also make use of the distance scalar variable OPENING which will continually reflect the distance between the fingers. An example:

```
OPERATE yfingers
    WITH OPENING = 2*IN
    WITH VELOCITY = 2*CM/SEC
    ON SQUEEZE > 3*OZ DO STOP
    ON OPENING ≤ 1*CM DO STOP
```

2.3 AFFIXMENT

2.3.1 THE AFFIX STATEMENT

Assembly often involves affixing one object to another. AL has a mechanism to automatically keep track of the location of a subsidiary piece of the assembly as its base is moved; the mechanism is called ***affixment***. For example, there might be a frame called pump and a frame called base. At some stage in the assembly, the pump is bolted to the base. At this time it is appropriate to include the statement

AFFIX pump TO base

This statement informs the compiler that motions of base are to affect the location of pump causes code to be generated for the runtime which will automatically update the value of pump every time base is changed. Finally, the planning model will be updated to reflect the affixment. A slightly more formal definition of affixment, in terms of explicit assertions and modifications to the runtime graph structure, is given in subsection 2.4.2.

Please note that the AFFJX statement does not act as a library routine invocation; it does not generate code to actually perform the bolting operation. The statement merely informs the AL system that at this stage in the execution of the program, pump is to be considered affixed to base.

If pump should be moved while affixed to base, the-value of base itself will not change, but the affixment will remain for the new relative positions of pump and base. Occasionally it is desired that the affixment be symmetric, so that motion of either frame will cause the other to move. This is done by including the reserved word RIGIDLY in the affix statement:

AFFIX pump TO base RIGIDLY

The system uses a trans to store the relative positions (in our example, (base → pump)) of the affixed frames. Normally, the system would invent a temporary variable to hold this trans; however, the user can supply his own variable to be used instead, thus allowing his to modify the affixment relation directly. This is done by including the phrase "BY <trans variable id>" in the AFFIX statement. For instance,

TRANS tl;

AFFIX pump TO base BY tl;

If the value of the trans is modified in a non-rigid (that is, asymmetric) affixment, the effect is to move the subsidiary frame. If the value of the trans changes in a rigid (symmetric) affixment, then neither frame will change its value until one of them explicitly gets a new value; at that time the other will spring to a new position, as determined by the trans.

The inclusion of the construct "AT <trans expression>" will cause AL to use the indicated value for the relative affixed position of the objects. Thus,

```
AFFIX pump TO base AT NJLTRANS
```

is equivalent to

```
TRANS tempxf;
AFFIX pump TO base BY tempxf;
TEMPXF ← NJLTRANS
```

Similarly,

```
TRANS XF;
AFFIX pump TO base BY xf AT TRANS(NILROT,Z);
```

is equivalent to

```
TRANS XF;
AFFIX pump TO base BY xf;
xf ← TRANS(NILROT,Z);
```

It is possible to make chains of affixments, possibly involving some rigid affixments and some non -rigid ones.

2.3.2 THE UNFIX STATEMENT

Affixments are undone by the UNFIX statement. For example,

```
UNFIX pump FROM base
```

will remove the affix structure between pump and base, and will discard the invented trans (unless it was named, of course>. Similarly, the compiler's planning model will be updated to reflect the fact that pump and base are no longer affixed. However, the fact that they were previously affixed is important for calculation of default "deproaches" (Section 2.2.5), and is remembered until either of the two frames is changes. See subsection 2.4.2 for a more detailed description of the assertions actually made do do this.

2.3.3 MOTIONS AND AFFIXMENT

When some frame has been affixed to an arm, it can be treated as if it were itself an arm. Thus, the following is legal and useful:

```
FRAME frob, frobgrasp;

AFFIX frobgrasp TO frob;
AFFJX frob TO yellow;

MOVE frobgrasp TO ⊗ + (Z WRT frob);
```

The effect of this motion statement is to cause the yellow arm to move in such a way that frobgrasp moves one centimeter in frob's **Z** direction. The compiler notices that frobgrasp is affixed to frob, which in turn is affixed to yellow; furthermore, it knows the relative positions of each of these, so it is not too hard to translate the given motion statement into a statement dealing only with the yellow arm. It is a great convenience to let the compiler do this translation, which can get messy in the presence of complicated affixment structures.

The use of "⊗" inside a motion always refers to the frame being treated as an arm, whether it is actually an arm (blue, yellow) or an affixed frame (frobgrasp).

If some frame is attached to more than one arm, then it is not legal to use this feature, because the compiler would have no way of determining which arm to use. Actually, such an attempt is most **likely** an error on the user's part; if an object is affixed to both arms, then they are joined through that object. It is therefore not safe to move one arm and not the other. The "right" thing to do in such a case would be move all the relevant arms to the appropriate places. We do not intend to implement this at first.

2.4 GRAPH STRUCTURES

Affixments are stored in both the compiler and the **runtime** by means of a *graph structure* which is used to assure that variable values are consistently updated. The actual algorithms used for this process are given in Appendix III. Essentially, the **runtime** system keeps track of dependencies between variables. If a variable value is changed, any variables which depend on it are marked as "invalid". Then, whenever the value of an "invalid" variable is needed, the **runtime** system will attempt to recompute it from the dependency information. If this attempt fails (as might happen if two "invalid" variables depend on each other) then the current ("invalid") value is used as the best answer available.

2.4.1 EXPLICIT MODIFICATIONS .TO THE GRAPH STRUCTURE

The dependency information principally consists of a list of arithmetic expressions that may be used to calculate the new value of a variable, together with a list of statements to execute whenever the variable is changed. (In addition, the **runtime** keeps with each variable a list of all other variables whose values may depend upon that variable). Generally, this information will be updated implicitly as part of the AFFIX and UNFIX statements. However, AL does provide statements for updating the structure explicitly. The principal statement employed for this purpose is the *graph assignment statement:*

<variable> **<=** <expression>

where "**<=**" may be read "is computed by". This construct causes <expression> to be added to the list of calculators for **<variable>**. Also, it causes the left hand side **<variable>** to be added to the dependents list of any variables that may occur in the <expression>. Thus,

```
FRAME f1, f-2;
TRANS t;
f1 <= t:f2;
```

says that f1 is computed by the expression "t:f2" and, hence, depends on t and f2. Note that graph assignment is cumulative, so that

```
a <= b:c;
a <= d+e;
```

would cause a to be marked invalid whenever b, c, d, or e is changed. In such a case, it is undefined whether "b:c" or "d+e" would be used to recompute a, assuming that all of the variables were valid when the value of a is needed.

The statement

<variable> <≠ <expression>

causes <expression> to be removed from the list of calculators and makes the appropriate modifications to the dependency lists. Similarly,

<variable> <<= <expression >

replaces the current calculator list for <expression>. The statement

<variable> <<=;

would cause the calculator list to be set to null.

In addition to the calculator list, a list of *updater* routines is associated with every variable. These routines are executed whenever the variable value is changed. Initially, the list of updaters is empty. However, the construct

WHEN CHANGING <variable> ALSO DO <label>: <statement>;

will cause the statement to be added to the list of updaters for the variable. The label is optional, but is necessary if the statement is ever to be removed from the updater list. In <statement>, the reserved words OLD and NEW may be used to refer to the old and new values of var, respectively. For instance:

```
, WHEN CHANCING f2 ALSO DO foo: f1 ← NEW:(OLD → F1);
```

Updaters may be removed from the updater list by the statement

WHEN CHANCING <variable> DONT DO <label>

For our above example, this would be

WHEN CHANGING f2 DONT DO foo;

The form

WHEN CHANGING <variable> ONLY DO <statement>;

replaces the updater list with one containing just <statement>, and

. WHEN CHANGING <variable> ONLY DO ;

clears the updater list completely. Since the affix structure makes use of updater and calculator lists (see subsection 5.2.2), careless use of the replacement form is not advised.

One possible use for updater routines is tracing. For example,

```
WHEN CHANGING v ALSO DO
    WRITE("The value of V is now ",NEW);
```

One additional point that should be mentioned here is that the updater routines for a variable are *not* called if the variable's value is modified as a side effect of a change to some variable in one of its calculators.

2.4.2 *GRAPH STRUCTURES AND AFFIXMENT*

As mentioned in the previous section, the AFFJX & UNFIX statements modify the graph structure. In fact, these statements may be be defined in terms of their effects on graph structure. Thus,

AFFIX f1 TO f2 BY t1

is equivalent to

```
t1 ← f2 → f1;
f1 <= t1 : f2;
WHEN CHANGING f1 ALSO DO yyy:t1 ← (f2 → NEW);
```

One additional effect of AFFIX is to cause the compiler's planning model to be updated by the addition of a symbolic assertion:

ASSERT FORM(AFFIXED, f1, f2, NONRIGIDLY, t1);

Such assertions are described more fully in Section 3.4. Essentially, all this one does is record the fact that the two frames have been affixed. This information is used in calculating deproaches (Section 2.2.5) and by several other parts of the compiler, and is also available to the user.

Similarly,

UNFIX f1 FROM f2;

is equivalent to

```
f1 <≠ t1*f2;
WHEN CHANGING f1 DONT DO yyy;
DENY FORM(AFFIXED, f1, f2, ANYTHING, ANYTHING);
ASSERT FORM(WAS_AFFIXED, f1, t-2);
```

The latter assertion is used in calculation of default deproach points. A side-effect of any assignment, like "f1← <value>", is

```
DENY FORM(WAS_AFFIXED, ANYTHING, f1);
DENY FORM(WAS_AFFIXED, f I, ANYTHING)
```

Rigid affixments, such as

```
AFFIX f1 TO f2 BY t1 RIGIDLY
```

are equivalent to

```
t1 ← f2 → f1;
f1 <= t1 * f2;
f2 <= INVERSE(t1) * f1
ASSERT FORM(AFFIXED, f1, f2, RIGIDLY, t1);
```

2.5 CONTROL STRUCTURES

2.5.1 TRADITIONAL STRUCTURES

AL has many of the traditional Algol control structures, including *statements, blocks, conditionals,* and loops. There are no *jumps* in AL, because they confuse the flow analysis needed for maintaining planning values and because it is possible to accomplish much without them.

We have already seen some applications of block structure. More formally, a *block* is a list of *statements*, separated by semicolons, and surrounded by the reserved words *BEGIN* and END. The entire block is treated syntactically as a statement; thus, its definition is recursive. One particular kind of statement is the *declaration.* We have already seen declarations for algebraic variables. There are a few rules pertaining to variables and declarations: Every variable must be declared at some point in the program before it is used. Declarations may appear anywhere in a block; there is no restriction that they must precede other statements. The local block of a variable is the block defined by the narrowest BEGIN-END pair which surrounds its declaration. Blocks defined by narrower BEGIN-END pairs are called *inner* blocks, and those defined by wider pairs

are called *global* blocks. The primary rule is that variables may only be referenced in their own local or inner blocks. Another way to state the same thing is that within any given block, it is only legal to refer to variables declared locally or globally to that block.

Here is a simple example which demonstrates the other standard ALGOL control structures:

```
sample: BEGIN (Meaningless example)
    SCALAR a, i;
    a ← 2;
    FOR i ← 1 STEP 1 UNTIL 10 DO a ← a*a;
            {This is very likely to cause arithmetic overflow!}
    WHILE a > 0 DO
    loop: BEGIN
        a ← a - 1;
        IF a < 5 THEN WRITE(a) ELSE WRITE(a-5)
        END loop;
    W R ITE("Done")
    END sample
```

Even though there is no jump instruction, there are labels; they are useful during debugging, for naming condition monitors, and for some other purposes which we will see later. It is good practice to name blocks, and to repeat the name after the closing END; this allows the compiler to check that the proper **BEGIN**s and **END**s match.

The FOR *loop* is quite traditional; it follows the form:

FOR <s var> ← <s expr> STEP <s expr> UNTIL <s expr> DO <statement>

where <s var> stands for "(possibly dimensioned) scalar variable" and <s expr> stands for "scalar expression of compatible dimension". The initial value of the variable is the value of the first expression; every time the statement is executed, its value is incremented by the value of the second expression, and the process repeats until the value exceeds that of the third expression. If the step size is negative, the right things happen. A test is made before the first iteration, so it is possible that the loop will not get executed at all.

The *WHILE* loop is another means to control iteration. It syntax is this:

WHILE <condition> DO <statement>

where the condition is some boolean expression involving one of the operators $<, >, \leq, \geq, =$, and $\neq$. Boolean expressions can be built up out of such arithmetic operators, the logical connectives $\wedge$ *(and)*, $\vee$ *(or)*, $\neg$ *(not)*, and the logical constants *true* and *false*. The first check is made before the first iteration; the statement is executed repeatedly until the condition fails.

The *conditional statement* has the form:

```
IF <condition>
    THEN <statement>
    ELSE <statement>
```

The ELSE part is optional. The <condition>, which is just like the condition in a WHILE statement, is evaluated; if it is *true,* the THEN part will get executed; if it is *false,* the ELSE part (if there is one) gets executed.

The *conditional expression* is much the same as the conditional statement:

```
IF <condition>
    THEN <expression>
    ELSE <expression>
```

This can be used whenever an expression is needed.

2.5.2 COBEGIN-COEND

In addition to traditional ALGOL structures, there are also some additional ones for more sophisticated flow of control. The first such construct is the ***COBEGIN-COEND*** pair, which brackets statements whose execution is meant to occur independently. Each of the statements within the *simultaneous* block will eventually get executed, but there may be considerable overlap of execution. For example, while one arm is moving, another statement can be computing; several arms can also work at the same time. The termination of the block occurs only when all of the statements in the scope of the COBECIN have terminated. Declarations should not be included as local statements in the region of simultaneity. It is not particularly useful to have simultaneous execution of a purely computational code; the real reason for the COBEGIN construct is to allow simultaneous independent manipulator control. Here is a simple example:

```
swing: COBEGIN {Wish to get all three arms to their rest positions.)
    MOVE yellow TO ypark;

    MOVE blue TO bpark;

    MOVE red (rue should Aave such an arm) TO rpark;
    COEND swing
```

2.5.3 PARTIAL ORDERING OF SVBTASKS

An assembly task is often divided into subtasks which enjoy a partial ordering with respect to the intended order of execution. For example, consider a task A which contains four subtasks, B, C, D, and E, of which B and C must be done before D, and D must be done before E, but B and C could be done in any order. It is possible in AL to leave the ordering of the subtasks up to the compiler, which will try to optimize the entire operation with respect to total expected time and economy of motion. For example,

```
a: TASK BEGIN {Sample of partial ordering on subtasks}
      b: BEGIN
         <code for task B>
         END b;

      c: <code for task C>;

   d_e: BEGIN (both D and E}
         <code for task D>
         <code for task E>
         END d_e;

PREREQUISITE OF d_e IS c;
PREREQUISITE OF d_e IS b;
END
```

The words TASK BEGIN introduce a *task* ***block,*** which contains a set of statements, The prerequisite statement

PREREQUISITE OF <label1> IS <label2>

informs the compiler that the statement identified by <label2> must be done before the statement identified by <label1>. One important restriction is that both statements so named, as well as the prerequisite statement itself, must all occur in the same TASK block.

The order in which the statements are performed is determined only insofar as the prerequisite conditions demand. The compiler may reorder them consistently with the preconditions, and may even execute some of the statements simultaneously (as if there were a COBEGIN), if this is feasible.

As can be expected, it is rather difficult for the compiler to keep track of planning values in the vicinity of a TASKBEGIN. For this reason, it is a good idea to make heavy use of the planning value assignment statement (the one with the double arrow: "←←"; see Section 3.2) to keep the compiler informed of what is intended to be true, both within the partially ordered block and immediately afterwards.

2.5.4 EVENTS: SIGNAL AND WAIT

To achieve simultaneous coordinated motion, one uses a special form of the move commands which will be discussed later. However, some simple synchronization is possible within the context of simultaneous execution. This is achieved by means of explicit events, which can be signaled and awaited. Every different event that the user wishes to use should be declared. For instance,

EVENT e1, e2, e3

With each event is associated a count of how many times it has been signalled. Initially, the count is 0, that is, no signals have appeared, and no process is waiting. The statement

SIGNAL el

increments the count associated with event el, and if the resulting count is 0 or negative, one of those processes waiting for el is released from its wait and readied for execution. The statement

WAIT el

decrements the count associated with event El, and if the resulting count is negative, the process issuing the WAIT is blocked from continuing until a signal comes along. If the count is 0 or positive, there is no waiting.

An example of the utility of this construct is inside a simultaneous block, where one path of execution requires that the other path has passed some milestone. Here is how such a use might appear:

```
EVENT milestone;
COBEGIN {Example of use of SIGNAL and WAIT)
 path 1: BEGIN
        <code before the critical point>
        WAIT milestone;
        <code after the critical point>
        END path 1;

 path2: BEGIN
        <code in preparation for the milestone>
        SIGNAL milestone;
        <code following the milestone>
        END path2
COEND
```

2.5.5 STATEMENT CONDITION MONITORS

We have already seen condition monitors in the context of motion statements. The same construct is of general utility; most of what was said before holds for the *statement condition monitor* as welt.

The conditions which may be tested in statement condition monitors are principally events, since DURATION, SQUEEZE, and FORCE are associated usually with a particular motion. As is the case with motion condition monitors, the statement condition monitors can be in two states: *enabled* and *disabled.* A monitor becomes enabled when its defining statement is executed, and becomes disabled when it triggers, is explicitly disabled by some other statement, or its local block is exited. The same conventions as have already been seen apply to the naming of condition monitors and

their explicit enabling and disabling. Scope rules come into play regarding what condition monitors it is permitted to enable or disable; the rule is that only condition monitors defined locally or globally to a piece of code can be touched by that code. The word DEFER still causes a condition monitor to be defined in an initially disabled state.

When a block is exited, all monitors local to that block are disabled. However, the block exit code will wait until the bodies of any triggered monitors are completed before disabling any monitors, deallocating local variables, or performing any of the other functions associated with block termination. If the execution of one of these triggered monitor bodies causes other monitors to trigger, then the block exit will wait for those, also. Furthermore, block exit is treated as an atomic process; all monitors are disabled at the same time.

The constructs CRITICAL and UNCRITICAL apply to statement condition monitors just as they do to motion condition monitors.

2.5.6 COMMENTS

The most standard way to insert comments in an AL program is to surround them with curly brackets, as we have done in all our examples so far. It is also legal to use the word COMMENT before a comment, and to end it by a semicolon. This type of comment may not contain any semicolon. The user can optionally reset the comment delimiters from "{}" to whatever she wishes, by means of a require statement such as

```
REQUIRE "%%" COMMENTDELIMITERS
```

which would cause the scanner to ignore any text between "%" signs. It is expected that this will seldom be needed.

2.5.7 LABELS

Labels specify points in the program;-they are useful for naming condition monitors, and subtasks. It also assists during debugging of programs. To label a statement, preface it (with an identifier followed by a colon. Labels are not declared.

```
foo: a ← a + 1;
```

2.5.8 *ABORT*

Occasionally the user wishes to stipulate that if the program ever reaches a particular point, something is hopelessly wrong. The statement ABORT causes the runtime to stop all moving devices and to terminate execution. The supervisor is informed of the halt, and will inform the

user. ABORT takes an optional string argument, which is a message which will be given to the user if the ABORT statement is executed. An example:

ABORT ("I keep missing the hole!")

2.5.9 OUTPUT

There are several ways that the user can request output from AL to the console. As mentioned above, ABORT can print a message during execution. There is another way to print a message during execution, the WRITE statement, which takes as arguments a list of variables and constants. It is also legal to include a string constant in this list (there are no string variables in AL,). Formatting of output is automatic. An example:

WRITE ("I think that the pump is at ",PUMP)

Some pieces of code are only intended to work under certain conditions of planning knowledge. Such code might have a check to insure that its preconditions are met; if not, it is proper to signal a compile-time error, with a message. This is done with the PLAN ERROR statement, which optionally takes a string argument, and which will halt compilation and print the message. One of the options the supervisor will give the user is to proceed as if no error had been encountered. Here is an example:

PLAN ERROR("Hey! You didn't attach the pump to the hand!")

A similar statement which merely prints its message but does not halt compilation is the PLAN WRITE statement, which behaves in all respects like the runtime WRITE statement in that it can take variables and constants in its argument list, but where variables are specified, the planning values will be printed. For example:

PLAN WRITE("Yellow arm should be at",yellow)

2.5.10 PROCEDURES

AL has only a limited capacity for procedures. All parameters to a procedure assume the planning value "undefined" at the conclusion of a procedure call, except those which are declared as VALUE parameters in the procedure heading, or those stated to be UNCHANGED in the procedure call. There is no safeguard against the accidental modification of "unchanged" parameters; to state "unchanged" is entirely equivalent to an assertion that the parameter has not changed its value during the execution of the procedure. The declaration of a procedure is this:

type PROCEDURE name (argument list)

where *type* is any data type (and is optional), and *argument list* is a list of parameter names with their types. An example:

```
DISTANCE SCALAR PROCEDURE lgth (FRAME fl, f2; VECTOR VALUE vl);
```

This declares that lgth is a procedure which returns a scalar, and takes as arguments two frames and one vector. The vector is not changed by the procedure.

To call such a procedure:

```
DISTANCE SCALAR sl;
FRAME frob, hole;
VECTOR vect;

sl ← lgth(frob, UNCHANGED hole, vect);
```

This further asserts that hole is not changed by the call.

It is a good idea to use the planning value assignment ("←←") heavily at the start of a procedure body to inform the compiler of the values to expect for the various arguments. Remember that trajectories planned on the basis of highly inaccurate planning values will not work well. As a procedure is entered, all variables have planning value "undefined". Globals may be accessed, but they also have undefined initial planning value. All variables which have explicit or implicit assignments within a procedure acquire the value "undefined" at the point directly after the procedure call.

No modification of the affixment structure is allowed inside a procedure. The compiler (often wrongly) assumes that there are no affixments involving variables within a procedure; it requires an assertion like

```
ASSERT FORM(AFFIXED, fl, f2).
```

to override this mistake. Affixments are discussed in Section 2.3 and more general assertions in Section 3.4.

There are four special types of procedure calls: A AL program might wish to call a routine coded for the mini or a routine coded for the timesharing machine. Likewise, a program on the timesharing computer may wish to control an AL program, or a routine on the mini may wish to request some arm motion.

To achieve the first two cases, there exist *external procedures* in AL. These are compiled into calls on either routines in the mini or routines in the timesharing computer's runtime package. To declare such a procedure:

```
EXTERNAL MAXI FRAME PROCEDURE foo (FRAME a, b; VECTOR v)
```

This declares the procedure foo to be a procedure resident in the runtime "maxi" (that is, timesharing computer) package, expected to return a frame value, and taking as arguments two

frames and a vector. Maxi procedures do not have access to the actual variables sent, since copies are made; therefore, all arguments to maxi procedures are considered to be VALUE parameters.

It is possible to declare untyped (i.e., statement-like, instead of expression-like) procedures as well. Replace "maxi" with "mini" for procedures in the mini. Such procedures do have access to values, and therefore parameters are not automatically considered to be VALUE.

To achieve the second two cases, there exist *internal procedures* in AL:

```
INTERNAL FORCE VECTOR PROCEDURE baz (SCALAR s);
```

Internal procedures must be at the top level of an AL program. A complete AL program is considered to be an untyped procedure without parameters.

CHAPTER3
COMPILE-TIME CONSTRUCTS

3.1 INTRODUCTION

AL seeks to maintain a fairly accurate planning model of the expected state for each point in the execution of a program. This planning model includes the expected values of runtime variables, together with a number of symbolic assertions about objects, relations between frames, constraints on trajectory endpoint conditions, and other information, and is important throughout the system. At the lowest level, it provides "target" locations for the calculation of proper trajectories. Beyond this, planning information is used to direct conditional expansion of input programs and library routines, and provides a basis for decisions on how to translate the various high-level, assembly-oriented constructs into runnable manipulation programs.

A number of language constructs are provided in AL to allow the user to access this model and to assist in maintaining it. These facilities are described in this chapter, which also discusses language features such as conditional compilation for increasing the convenience of programming and the flexibility of programs. The use of the planning model facilities for object descriptions and by the "very high level" components of AL is discussed more fully in Chapter 4.

3.2 PLANNING VALUES

One very important piece of information about a variable is its *planning value,* which is the compiler's estimate of what value the variable will have at some point in the program execution. As with other aspects of the planning model, planning values have many uses in AL. One especially important use is in trajectory calculation. Although provisions are made to modify any preplanned trajectory before executing it, the current scheme requires that at least a roughly accurate value be available at compile time if smooth trajectories are desired. This was discussed in subsection 2.2. 1.

Typically, planning values are updated whenever the compiler encounters something that it has reason to expect will cause the runtime value to change. For instance, the assignment statement

```
foo ← 3
```

will cause the compiler to emit code to set foo to 3 and will cause it to change the planning value of foo to become 3. Similarly

```
a ← b + c
```

will cause the planning value of variable a to be set to the planning value of *b* plus the planning value of c, provided that both *b* and c have known planning values. If one of the planning values isn't known, then *a* gets the special planning value *undefined,* which is also used as an initial planning value at the time a variable is declared.

Motion statements also can cause planning values to be updated. For instance,

MOVE yellow TO bar

will cause the planning value of yellow to be set to the planning value of bar. Also, the planning value of any variables affixed to yellow will be updated appropriately.

The planning value of a variable may be retrieved by use of the construct

*(<variable name>)

which yields a constant equal to the planning value of the variable. For example,

```
b ← 3;
a ← *(b);
```

has the same effect as

```
b ← 3;
a ← 3;
```

Although the compiler makes an effort to keep track of the expected runtime state of variables, it must sometimes be given explicit assistance. For example, it is difficult for the compiler to maintain unambiguous planning values over conditional statements, as in this example:

```
SCALAR s1, s2;
VECTOR v 1;
s1 ← 100;
IF s2 > 3 THEN
      BEGIN
      v1 ← VECTOR(1,2,3);
      s1 ← 101;
      {*(s1) = 101}
      {*(v 1) = VECTOR( 1,2,3)}
      END
ELSE
      BEGIN
      v 1 ←VECTOR(1,2,4);
      {*(v 1) = VECTOR(1,2,4)}
      {*(s1) = 100)
      END;
{*(v 1) = UNDEFINED)
{*(s1) = UNDEFINED)
```

Although the compiler may eventually be smart enough to resolve a number of such cases, for the moment the user must tell the compiler what planning value to use thereafter.

The compile-time assignment statement:

<variable> ←← <constant expression7

is provided to set the planning value of a variable. Such assignments affect only the planning value; no code is emitted, and the **runtime** value of the variable remains unaffected. Thus, both

v ← VECTOR(3,3,3)

and

v ←← VECTOR(3,3,3)

set the planning value of v to VECTOR(3,3,3), but only the first form causes the **runtime** value of v to be changed.

Planning values provide a useful way to generate error estimates, as in

```
FRAME fl, f2, f3;

AFFIX fl TO f2 RIGIDLY;

AFFIX f2 TO yellow;
MOVE yellow TO f3;
        (Moving the yellow arm will cause the runttme values of frames f1 and f2,
        which are affixed to it, to be updated as well.}
WHILE ABS(LOC(f 1)-LOC(*(f 1))) > .25*CM DO
    BEGIN

    (Make a correction)
    {M ensure f1}

    END;
```

Although it is theoretically possible for the user to fill in the relevant nominal values explicitly, in practice this can be rather inconvenient, especially when the planning values are derived from some complicated computation. Furthermore, the availability of planning values offers significant advantages with regard to program flexibility, since changing a particular expected value will not, in general, require substantial changes in program text.

3.3 PLANNING VARIABLES

Planning variables allow the user to take advantage of the compile-time computation and planning value maintenance facilities of AL without incurring the **runtime** overhead of having regular variables in cases where only their planning values are ever used. Typical uses include attaching symbolic names to constants, use of temporary variables in compile-time calculations, object modelling, access to symbolic assertions in the planning model, passing "advice" to **high-**level language primitives and to library routines.

3.3.1 ALGEBRAIC PLANNING VARIABLES

Algebraic planning variables are declared by the construct

PLANNING <data-type> <identifier 1>, . . . , <identifier n> .

For instance,

```
PLANNING SCALAR a, b, c;
PLANNING DISTANCE SCALAR d 1, d 1;
PLANNING FORCE VECTOR fl, f2, lift;
PLANNING TRANS t;
```

Such variables may have planning values, but have no **runtime** existence whatsoever. This means that they may appear on the left hand side of planning assignment statements (i.e., the "←←" form), but not of regular assignment statements (i.e., the "←" form). Similarly, a planning variable may not appear in an arithmetic expression, although its planning value (that is, *(<ct var>)) may do so. Thus, the following are legal:

```
PLANNING SIMPLE a, b;
SIMPLE v;

a ←← 3;
b CC +(a) - .01;
v ← 2 + *(a);
v ← w(v) - v**(b);
b CC UNDEFINED; {this causes b to lose its planning value)
```

These, however, are not legal:

```
PLANNING SIMPLE a, b;
SIMPLE v;

a ← 3;
v ← a; (Note that no coercions to planning values are ever made.)
b ← a; (Ditto)
v ← UNDEFINED; (UNDEFINED has no runtime meaning.)
```

3.3.2 *A TOM S*

In addition to the regular **runtime** data types, there are several additional types that (presently) can occur only with planning variables. These variables follow the usual rules concerning planning value assignment and propagation, except that their "value" is not an arithmetic quantity. Instead, it is the internal structure associated with some construct in the language. Perhaps the most important of these variable types is the *atom,* which is a variable whose (planning) value is the name of another variable. Atoms are declared by the construct

ATOM <id 1>, . . . , <idn>;

Note that the word "PLANNING" is not needed, since an atom is purely a planning construct. Planning values may be assigned to atom variables by use of the construct

<atom name> ←← <variable name>

as in

```
ATOM al, a2, a3;
DISTANCE SCALAR d;

al ←← d;
a2 ←← a3;
r(a2) ←← *(a 1);
        {Now, *(a1)="d", *(a2)="a3", *(a3)="d"}
```

Notice that *(<atom>) yields the name of a variable; its effect is as if the variable itself were used. Thus,

d ← 100*feet

and

*(a 1) ← 1 00*feet

will both have the same effect. Also, note that assignment to an atom constitutes the only case where the name of a variable may -appear on the right hand side of a planning assignment statement.

Atoms serve a number of useful purposes, the most prominent of which include serving as "key words" in symbolic assertions, providing a means for retrieving and using variables as object properties, and as a means for adapting the same piece of program text to perform different versions of the same task. For instance,

```
ATOM arm, h;
FR AM E hole 1 ,hole2;
.
arm cc blue;
h ←← holel;

MOVE *(arm) TO *(h);

h CC hole2;

MOVE *(arm) TO *(h);
```

Here, the MOVE statement has been typed out twice, so the actual saving is rather small. In practice, however, it is common to place such statements inside a macro or library routine (see Section 3.7), in which case the gain in convenience can be appreciable. Similarly, the atoms "arm" and "h" can be given planning values by means of the BIND construct in a planning conditional expansion (see Section 3.5).

3.3.3 EXPRESSIONS, CLAUSES, STATEMENTS, AND FORMS

Another very important type is the *expression,* which takes as its planning value the internal structure associated with an expression in the language. These variables are declared by the construct

```
EXPRESSION <id1>,. . . ,<idn>;
```

Again, note that the word "PLANNING' is not used. If desired, an atom or expression variable may be restricted to values of some particular algebraic type by inclusion of the appropriate additional declarators. For instance,

```
DISTANCE ATOM da;
VECTOR ATOM va;
FORCE VECTOR ATOM fva;
TRANS EXPRESSION te1, te2;
```

Other planning only types include *statement, clause,* and *form.* Statement variables take as their planning values the internal structure associated with a statement. Clause variables take as their planning values the structure associated with clauses, such as "TO ⊗" and "WITH DURATION ≥ 3*SEC". Clauses, statements and expressions are primarily useful as a means of passing explicit "advice" on to a library routine or high-level primitive. In addition, statement variables are frequently very useful as placeholders in partially written code.

Form variables hold references to assertions in the compiler's planning model and are discussed in more detail in subsequent sections. One use is to allow a user to remember the name of an assertion in such a way as to facilitate undoing it later.

Planning values may be assigned to clause, statement, expression, and form variables by use of the appropriate construction functions to produce constants of the appropriate types. Thus we might have:

```
TRANS tl;
FRAME widget;
ATOM height;
CLAUSE c;
EXPRESSION e;
STATEMENT s;
FORM f;

'f ←← FORM(height, widget, 100);
e ←← EXPRESSION(t l::ypark);
s cc STATEMENT(MOVE YELLOW TO *(e));
c ←← CLAUSE(VIA widget);
```

*(Note that *(e) will not be evaluated until the planning value of s is used; that is, until *(s) is used as a statement somewhere)*

As one might expect, the argument to an *expression* primitive is an expression, the argument to *clause* is a clause, and and the argument to a *statement* primitive is a statement. These compile-time functions return the internal structures associated with their arguments; when this structure is stored into a planning variable of the appropriate type then the planning value of that variable becomes the expression or statement. Thus,

```
e ←← EXPRESSION(t l::t2::f 1);
c ←← CLAUSE(VIA widget);
s cc STATEMENT(MOVE YELLOW TO f3 *(c));
:
f3 ← *(e)
*(s);
```

and

```
f3 ← t l::t2::f 1;
MOVE yellow TO f3 VIA widget;
```

will have exactly the-same effect.

3.4 ASSERTIONS

In addition to planning values, the planning model used by AL includes a number of facts that are usefully expressed as symbolic assertions. These facts include object descriptions, semantic information about what is in the hands, state information about required approaches for motions,and relations between frames. Internally, all facts (whether added to the data base by the compiler or explicitly by the user) are represented as forms of constant elements such as one might find as planning values for some variable or another. For example,

```
FORM(Roses, are, red);
FOR M(W EIGHT, engine-block, 3.5*POUNDS);
FORM(AFFIXED, fl, TO, f2, BY, t3, RIGIDLY);
FORM(v 1, COMPUTED-BY, EXPRESSION(a*v2+v3));
```

are typical of the sort of forms which one might have in the data base.

Readers familiar with recent research in artificial intelligence will no doubt recognize the similarity of many of the constructs presented in this section with comparable features in modern AI languages. A detailed discussion of this relation or of implementation details is beyond the scope of this paper. However, perhaps it should be pointed out again that the assertion mechanisms in AL are a planning-time construct without any runtime existence. The system attempts to keep track of what facts are expected to be true at each point in the program by associating with each fact in the data base a set of "worlds" corresponding to each place that a fact is true. Some further discussion of this mechanism may be found in Section 4.5.

3.4.1 THE ASSERT STATEMENT

Symbolic assertions may be added to the data base by use of the statement

```
ASSERT <form>
```

where <form> is either the planning value of a FORM variable or a call on the FORM construction primitive,

```
FORM(<element 1>,<element 2>, . . . ,<element n>)
```

In general, each <element> must be something that can appear on the right hand side of a planning assignment statement (i.e., the "←" assignment). This includes constants, expressions involving only constants (including &variable>)), variable names, and the results of construction functions like EXPRESSION, STATEMENT, and FORM. (Also, the BIND construct is allowed, but this is discussed later). For instance,

```
ATOM holds, SLOT, headtypel, HEX, now, is, the, time;
        (We are following a convention that individuals are in lower case, and classes
        or properties are in upper case.)
STATEMENT PARKING-METHOD;
FRAME driverl;
FORM formvar;

ASSERT FORM(yellow, holds, driver 1);
ASSERT FORM(SLOT, headtypel, HEX, 0.53);
ASSERT FORM(PARKING_METHOD, yellow,
            STATEMENT(MOVE YELLOW TO YPARK));
formvar ← FORM(now, is, the, time);
ASSERT +(formvar)
```

The actual meaning of an asserted pattern is generally determined by whatever conventions the user may wish to establish. However, a few pattern types, such as those for affixment or those used by the very high level routines for object descriptions, are "understood" and used by the compiler. (As mentioned earlier, AL includes a number of predeclared atoms to act as key words in these reserved patterns.) The user can cause serious confusions by improper introduction or deletion of such patterns, although, used properly, they provide a valuable tool for communication with the planning model.

3.4.2 THE DENY STATEMENT

Generally, assertions will remain "true" in the compiler's world model until explicitly deleted or, in the case of assertions used by the compiler, as a side effect of processing some statement. Any assertion may be undone by use of the DENY construct, which is similar to ASSERT:

```
DENY FORM(IN, HAND, screwdriver);
DENY *(formvar);
```

3.4.3 CONSTRAINT ASSERTIONS

In addition to planning values and symbolic assertions, the system's planning model may include constraint information delimiting the range of values that a variable may take on. Much of this information is expressed internally by means of mathematical constraints on scalar variables that represent degrees of freedom in object locations. For instance, if a flat surface of an object is flush up against another flat surface, then (in the absence of other constraints) the object will have two translational and one rotational degrees of freedom. These constraints are generally derived from the semantics of the various "high level" operations, the object descriptions, and certain "standard" assertional patterns. (See Section 4.6 for more details.) In addition, however, a user can use the construct

```
ASSERT <expression><relation><constant>
```

in order to state a constraint relationship explicitly. The <relation> may be any of "≤","<","=",">", and "≥". At present, <expression> is restricted to be a linear form involving only scalar variables or the dot product of two vectors. For instance,

```
DISTANCE SCALAR a, b, c;
VECTOR v;

ASSERT 3*a + 4*b - 2*c ≤ 2*INCHES;
ASSERT v . Z > 0.25;
```

This construct is primarily intended for use in debugging the higher level operators and in writing library routines that are to be used with such operators. It is being described here in the interests of completeness and because reference is made to it in Section 4.6.

3.4.4 STANDARD USES FOR ASSERTIONS

The user may use the assertional database to store arbitrary information. Certain patterns, however, are given special meaning in AL. For example, in our discussion of **deproaches**, we implied that the compiler keeps track of each frame's associated deproach by means of assertions. Thus, to give the frame f 1 a deproach transformation **t1**, one writes:

ASSERT FORM(DEPROACH, f 1, t I)

Another standard use is for affixments. One effect of the statement

AFFIX fl TO f2

is the assertion

ASSERT FORM(AFFIXED, fl, f2)

Similarly, the object descriptions used by the assembly-oriented operations, as well as the planning model associated with such operations, rely quite strongly on standard assertion patterns. A fuller discussion of some of these patterns may be found in Section 4.7. However, this document does not purport to list fully all the patterns that are actually used by AL, although it should give the reader some idea of their approximate extent and should provide a fair indication of how they are actually used.

3.5 CONDITIONAL EXPANSION

It is frequently desirable to write a **fairly** general piece of source code that produces different object code, depending on the specific task to be performed and on the compiler's model of the expected **runtime** environment.

3.5.1 PLAN IF

The principal mechanism provided for this purpose is the plan-time conditional construct, which behaves like a conventional **Algol** "IF", except that it is resolved at compile time, with only the the "expanded" part having any effect on the compiler's world model. The syntax is:

```
PLAN IF <condition> THEN
        <then-part>
ELSE
        <else-part>
```

where the "ELSE" component may be omitted if desired. The condition may be any boolean expression which can be completely evaluated at plan-time. For instance:

```
PLAN IF *(blue) ≠ bpark THEN
        MOVE blue TO bpark;
```

which says that if the planning value of the blue arm is not equal to bpark (that is, if the last motion statement for the blue arm was not to its parked position), then insert a statement to move it there. Similarly, suppose we have a general routine for putting screws in holes. Further, assume that we are using a plan-time variable "chamfer" to contain the width of chamfering around the hole. Then the routine might have something like:

```
PLAN IF *(chamfer) > .25*INCHES THEN
        BEGIN
                (Code to perform a simple "straight in" insertion)
        END
ELSE
        BEGIN
                (Code to perform some sort of a search to get the screw into the hole}
        END;
```

3.5.2 TESTING FOR ASSERTIONS

The presence in the data base of a symbolic form can be tested by use of the *asserted* construct, as in

```
PLAN IF ASSERTED(FORM(IN,TOOLRACK,SCREWDRIVER)) THEN
        BEGIN
                (Code to fetch the screwdriver out of the tool rack}
        END;
```

In general,

ASSERTED(<form>)

returns "true" whenever the <form> is asserted in the planning model at the point that the test is made. Thus,

```
FORM f;
TIME t;

PLAN IF ASSERTED(+(f)) THEN
        BEGIN
        t←3*SEC;
        DENY *(f);
        END;
PLAN IF ASSERTED(*(f)) THEN
        BEGIN
        t←4*SEC;
        END;
```

would expand into

```
FORM f;
TIME t;

t←3*SEC;
DENY r(f);
```

Furthermore, note that ASSERTED(<form>) acts like a boolean primary and can enter into boolean expressions in the usual way. For instance,

```
PLAN IF ASSERTED(FORM(GOES_IN,shaft 1,hole 1))
            ∧¬ASSERTED(FORM,IN,shaft 1,hole 1)) THEN
        BEGIN
        PLAN IF ASSERTED(FORM(THREADED,shaft 1)) THEN
                BEGIN
                    (code to insert a threaded screw)
                ASSERT FORM(SCREWED,shaft 1);
                END
        ELSE
                BEGIN
                    (code to insert a smooth pin)
                -ASSERT FORM(SLIPPED_IN,shaft 1);
                END;
        ASSERT FORM(IN,shaft 1,hole 1);
        END;
```

3.5.3 THE ANYTHING CONSTRUCT

Frequently, one may want to test a whole class of asserted forms at once. For instance, suppose we may want to know if the blue hand is available for some task or another. We can keep track of what is in the hand by means of assertions like

ASSERT FORM(blue,HOLDS,widget);

However, it is frequently inconvenient, and sometimes impossible, to test all possibilities explicitly, as in:

```
PLAN IF   -ASSERTED(FORM(BLUE,HOLDS,widget))
  , A -ASSERTED(FORM(BLUE,HOLDS,frob)) ∧ . . . THEN
          BEGIN
          (whatever)
          END;
```

The reserved word ANYTHING is provided as a wild card to avoid this difficulty. Thus, we can write:

```
PLAN  IF  -ASSERTED(FORM(BLUE,HOLDS,ANYTHING))  THEN
      BEGIN
      {whatever}
      END;
```

One restriction of the current implementation is that one is not allowed to assert forms containing wild card elements like ANYTHING or the BIND construct discussed in the next section. One can only use them in constructs like ASSERTED, which don't try to add anything to the data base.

3.5.4 BINDING BOOLEANS

Frequently a simple wild card element like ANYTHING does not suffice. For example, the user may want to execute different code, depending on what is supposed to be in the blue hand. This situation is provided for by the use of

BIND(<ct variable>)

as one or more of the elements in a FORM pattern being tested by the ASSERTED construct. Generally, BIND(var) acts like a "wild card" that matches any element in the correct position in a form that has the same type as var. It has the additional side effect of setting the planning value of var to be the value of the element it matched. For example,

```
ATOM thing;
PLANNING FRAME where;

ASSERT FORM(blue,HOLDS,frob);
ASSERT FORM(CORRECT_SPOT_FOR,frob,FRAME(ROT(Y,180),VECTOR(1,2,3)) );
ASSERT FORM(CORRECT_SPOT_FOR,widget,
                    FRAME(ROT(Y,180),VECTOR(4,5,6)) );

PLAN IF ASSERTED(FORM(blue,HOLDS,BIND(thing)) ) THEN
    BEGIN
    (Here, #(thing) will get "FROB"}
    IF ASSERTED(FORM(CORRECT_SPOT_FOR,#(thing),BIND(where))) THEN
        BEGIN
        MOVE blue TO #(where);
        {some more code)
        END
    ELSE
        BEGIN
        (some sort of error message, perhaps)
        END;
    END;
```

Would expand into

```
MOVE blue TO FRAME(ROT(Y,π*RAD),VECTOR(1,2,3));
(some more code)
```

This construct is especially useful for library routines, which can use it to retrieve properties of objects and then take appropriate action.

3.5.5 PICK

One frequent use of assertions in. to specify a number of properties of some object or variable. For instance,

```
ASSERT FORM(HEIGHT,widget,100*CM);
ASSERT FORM(WEIGHT,widget,200*GM);
ASSERT FORM(DEPROACH,widget,FRAME(ROT(Y,π*RAD),X));
```

These properties can, of course, be retrieved by means of the ASSERTED construct, as in

```
PLAN IF ASSERTED(FORM(HEIGHT,widget,BIND(h)) ) THEN
        BEGIN
        MOVE YELLOW TO widget + *(h);

        END
ELSE
        BEGIN
        (perhaps some sort of error message]
        END
```

Unfortunately, this sort of thing can be rather inconvenient for fetching values, since it requires explicit use of an auxiliary variable and a fairly long statement. In such cases the PICK construct can be used instead, as in

```
MOVE yellow TO widget + PICK(FORM(HEIGHT,widget,BIND(*)) )
```

In general, PICK has the form

```
PICK(<form pattern>)
```

where the <form pattern> contains "BIND(*)" as *one* of its terms. PICK causes the compiler to retrieve a form that is in the planning model and which matches the template provided by the <form pattern>. The value in the form from the data base corresponding to the "BIND(*)" term in the template pattern is then returned as the value for PICK. Note that the argument template can also contain additional instances of ANYTHING and BIND(<variable>). These are bound in the usual way. For instance,

```
ASSERT FORM(gadget,fits,onto,widget,at,FRAME(NILROT,X) );

obj ←← PICK(FORM(gadget,fits,onto,BIND(*),ANYTHING,BIND(locn)) );
```

would set the planning value of obj to "widget" and that of locn to FRAME(NILROT,X).

3.5.6 PLAN FOREACH

Sometimes, there may be several assertions in the data base that could satisfy a given FORM retrieval pattern. For instance,

```
ASSERT FORM(s1,SCREWS,INTO,h1);
ASSERT FOR M(s2,SCREWS,INTO,h2);
ASSERT FORM(s3,SCREWS,INTO,h3);

PLAN IF ASSERTED(FORM(BIND(s),SCREWS,INTO,BIND(h))) THEN
        BEGIN

        END
```

In such cases, the compiler would arbitrarily pick one of the eligible patterns to use as its template for performing any requested bindings. Suppose, however, that the user wants to perform some action for *each* pattern that matches, rather than for only one. For instance, he may want to insert all the screws into their corresponding holes. The PLAN FOREACH construct is intended to allow this sort of thing.

```
PLAN FOREACH <form> DO
    <statement>
```

This construct will cause <statement> to be compiled once for each instance of <pattern> that finds a match in the data base.

For instance, a library routine that fastens down a head to an engine block by means of bolts which can be inserted in any order might include a sequence like:

```
ATOM bolt, hole_id, head_id;

PLAN FOR EACH FORM( BIND(bolt),FASTENS,*(head_id)) DO
    BEGIN
    PLAN IF ASSERTED(FORM(*(bolt),FITS,INTO,BIND(hole_id))) THEN
        INSERT *(bolt) INTO *(hole_id)
    ELSE
        BEGIN
        PLAN ERROR(bolt,"doesn't fit into",hole_id);
        END;
    END;
```

If we then have assertions:

```
ASSERT FORM(b1,FASTENS,pumphead);
ASSERT FORM(b2,FASTENS,pumphead);
ASSERT FORM(b3,FASTENS,pumphead);
ASSERT FORM(b 1,FRITS,INTO,h1);
ASSERT FORM(b2,FITS,INTO,h2);
ASSERT FORM(b3,FITS,INTO,h3);
```

and call our library routine to put on pumphead, the above fragment would expand into

```
INSERT b1 INTO hl;
INSERT b2 INTO h2;
INSERT b3 INTO h3;
```

3.6 THE COMPILE-TIME CHECK STATEMENT

Since library routines will be commonly used, it is necessary to have some way of checking that necessary preconditions are met as the first steps of the library routine. The way this is done is with the check statement. A simple example:

```
CHECK *(s1)=3 A *(s2)>5
```

The contents of the check may be any boolean expression, including checks on the current world model. The check is only made at compile-time; if the check is not satisfied, the compiler will generate an error message. The effect of this statement is exactly like that of

```
PLAN IF ¬(*(s1)=3 A *(s2)>5 THEN
    PLAN ERROR("Check statement failed")- .
```

3.7 LIBRARY ROUTINES

Many of the applications for which AL is intended characteristicly involve repeating a number of very similar subtasks. For instance, an assembly program might have to change sockets on an electric driver many times in order to drive down a number of different bolts. If written in "simple" AL, with each such subtask coded out in explicit statements like MOVE and OPERATE, such programs would be very tedious to write and debug. On the other hand, the necessity of planning motions frequently makes procedures (in the traditional sense) infeasible. To overcome this difficulty, AL provides a facility for "routines", which externally resemble macros, in that they are "expanded" each time they are invoked, although they are are stored and manipulated by the compiler in a somewhat more efficient manner. The AL system will include a predefined library of routines for performing a number of commonly useful functions, although a user can, of course, "roll his own" by using the ROUTINE construct, which has the form

```
ROUTINE <id> (<parameter list>);
    <body>
```

where the <parameter list> syntax is the same as for procedure definitions, and the <body> may be either an expression or a statement. When the library routine is expanded, all instances of the parameter names are substituted with the actual parameters supplied in the call. Thus, a typical library routine declaration might look like:

```
ROUTINE reach(SCALAR thickness;FRAME place);
    BEGIN
        (causes the hand to move to the indicated spot, and keep opening &
        closing its fingers until something is put in them)
    SCALAR flag;
    MOVE YELLOW TO place;
    flag← 1;
    WHILE flag ≠ 0 DO
        BEGIN
        OPERATE YFINGERS WITH OPENING = 5;
        OPERATE YFINGERS WITH OPENING = thickness-. 1
            ON YTOUCH DO
                BEGIN
                flag←0;
                STOP;
                END;
        END;
    END
```

Library routines without parameters are invoked simply by including their name in the source program. For instance, suppose we have a library routine PARK-YELLOW which parks the yellow arm. Then

```
IF h>3 THEN
    PARK-YELLOW
```

might expand into something like

```
IF h>3 THEN
    MOVE YELLOW TO YPARK
```

There are several ways to specify parameters. Perhaps the simplest is to follow the **syntax** for procedure calls, in which case the arguments must correspond in order and type with those in the statement which defined the routine. For example,

```
reach(0.5, FRAME(ROT(Z,90*DEG),VECTOR(1,2,3)))
```

This can become very inconvenient for routines which have a large number of parameters, since the user may have trouble remembering the correct order, or may want to leave some unspecified. These difficulties are avoided by using the form

```
reach(thickness = 0.5, place = FRAME(ROT(Z,90*DEG),VECTOR(1,2,3)) )
```

It is possible to specify default values for parameters to library routines by including the construct

```
(DEFAULT <value>)
```

after the parameter **name** in the formal parameter list for the routine. For example,

```
ROUTINE reach(FRAME arm(DEFAULT YELLOW),place;
                    SCALAR thickness(DEFAULT 0));
    BEGIN

    END


reach(BLUE,f 1); (A thickness of 0 is assumed.)
reach(place=f2,thickness= 10); (YELLOW arm assumed.)
```

The construct

```
SPECIFIED(<parameter id>)
```

may be used in a compile-time conditlonal to test whether the named parameter has been assigned a value. For example,

```
ROUTINE transmogrify(ATOM errdev;...);
    BEGIN
        (Note here that the atom errdev is merely being used as a name passing
        mechanism.)

    IF errcond THEN
        BEGIN
        PLAN IF SPECIFIED(errdev)
            THEN OPERATE (errdev)
            ELSE ABORT
        END;

    END;
```

If a parameter has no default value specified and is not bound by the call, then any expansion of the routine that uses the parameter will result in an error; occurrences of an unbound parameter in the unexpanded part of a planningconditional are legal.

Yet another syntax is acceptable for invocation of library routines; it is included for compatibility with high level primitives (see Chapter *4).* In this form, the parameter names act like key words identifying various clauses in a "pseudo-english" statement, as in

```
REACH thickness 0.5 place FRAME(ROT(Z,90*DEG),VECTOR(1,2,3))
```

If a parameter to a routine occurs in the body in some construct where a variable must occur (eg. the left hand side of an assignment statement), the compiler will do the "right' thing when the corresponding actual parameter is a constant or expression: a warning will be printed, and the compiler will invent a temporary variable to hold the value.

3.7.1 SAVING LIBRARY ROUTINES

Library routines may be saved on a file by use of the statement (and supervisor command)

SAVE <flag> <routine name list> ON <file specifier>

where <flag> may be either NEW, OLD, or <empty>. For instance,

```
SAVE reach, transmogrify ON "FEE.FIE[FO,FUM]";
SAVE OLD foobat ON "DEFS.1[11,HE]";
SAVE NEW grabl, grab2, grab3 ON "GRABS";
```

IF <flag> is <empty> and one of the named routines already exists on the specified file, the old definition is overwritten. IF <flag> is NEW, then only routines which do not already exist on the specified file will be added. Similarly, if <flag> is OLD then only routines which are already on the file will be saved. If the <routine name list> is omitted, then ail existing routines will be saved on the specified file. E.g.

```
SAVE ON "DEFS.ALL";
SAVE NEW ON "DEFS.2";
```

Library routines may be retrieved from a file by the command

RETRIEVE <flag> <routine name list> FROM <file specifier>

If <flag> is empty, then the specified routines will be retrieved from the specified file. If, however, <flag> is NEW, then only routines which are not already defined will be read in; if <flag> is OLD, then only routines which are already defined will be retrieved (they will be redefined), If the <routine name list> is <empty>, then all routines on the file will be read (subject to any restrictions imposed by <flag>). Examples:

```
RETRIEVE FROM "DEFS.RCB";
RETRIEVE Aeneas, Dido FROM "CAVE";
RETRIEVE NEW FROM "AL.LIB[AL,HE]";
```

3.7.2 SAVING AND RESTORING PLANNING VALUES

The statement SAVE WORLD ON W 1 will cause the "world" at that point in the planning to be written out into a file called W 1.WLD. The statement RETRIEVE WORLD FROM W 1 will read in this file and set up the world as it was when saved. The world includes all planning values and all assertions. It does not include defined library routines. Saving the world is particularly useful for recovering when the arm runs into trouble; it makes it unnecessary to begin the planning from scratch.

It is also possible to improve the planning values of frames after a period of execution; this is

done by the statement RESTORE WORLD FROM **RUNTIME**. The effect of this is that all the variables which the **runtime** knows about are read, and their values become the new planning values **for** those variables.

CHAPTER 4
VERY HIGH LEVEL LANGUAGE CAPABILITIES

4.1 INTRODUCTION

To date, manipulator control languages have been very explicit, with the user giving detailed specifications of what motions are to be made, what sensors are to be tested, etc. To some extent this is also true of AL. One can conceive of programming complicated assemblies using only MOVE and OPERATE statements, condition monitors, and the like. In practice, however, such an approach has many disadvantages for users, who frequently don't care about all the details needed to produce a program at the manipulator level. For instance, an assembly engineer who wants to put an engine together might typically want to write something like:

```
FIT enginehead ONTO engineblock
      WITH ALIGNMENT stud_x IN headhole_x,
                     stud-y IN headhole-y;
INSERT bolt1 IN headholel
      USING TOOL driver
      WITH TORQUE 10;
INSERT bolt2 IN headhole2
      USING TOOL driver
      WITH TORQUE 10;
INSERT drainplug IN sidehole;
```

and allow the system to fill in the details, rather than coding up all the motions herself.

This chapter gives an overview of those parts of AL that allow the user to specify tasks at somewhat more convenient levels -of abstraction than provided by the manipulation control statements alone. Here, we are concerned with a "semi-automatic" programming system that can make a number of the specific decisions required to turn an "high level" task description into a running program and which can ask for (and accept) help for those details that it cannot determine for itself.

The-range of decisions that the system may have to make is quite broad, ranging from very local matters, such as the number of trajectories which must be planned to ensure correct performance of all cases of some motion request, to rather global decisions, such as how an object should be grasped, how an object orientation is to be determined, or what should be the relative order for executing several related subtasks.

Some of these decisions are essentially domain-independent. For example, the system decides how many different arm trajectories it must plan for a given MOVE statement by examining its model

of the locus of the destination frame (see Section 4.6), without much regard for the "meaning" of the frame variable. Other decisions may require a significant degree of specialized knowledge about the task domain. For instance, the INSERT primitive in our example would need to know how a nutdriver is used to grasp a bolt, what effects (if any) the shape of the bolt tip or hole chamfer has on choice of search method, what constraints are imposed on workpiece positioning, and much more. One very important constraint on the output program is that it be consistent, in the sense that code generated to accomplish one subtask should not be inconsistent with (and, indeed, should facilitate) the accomplishment of other subtasks. This necessity, in turn, frequently generates further requirements for specialized knowledge about the requirements and effects of the primitives being provided.

We have chosen small scale industrial automation as a good domain for investigating the issues involved in incorporating such specialized knowledge into AL, and this discussion is oriented accordingly. However, many of the mechanisms underlying the various language features discussed here are fairly general; an expert system for some other manipulatory domain could be organized along the same lines and, indeed, could use at least some of the same primitives. The ease of such adaptation would depend, of course, on the closeness of the domains and on the particular primitives involved.

4.2 MACRO OPERATIONS AS A 'HIGH LEVEL LANGUAGE'

One obvious partial solution is to combine commonly occuring code sequences into "macro operations", and then allow the user to specify tasks in terms of those operations. AL includes sophisticated macro, defined routine, and conditional compilation facilities (see Chapter 3) for this purpose. Such library routines have the advantage of being relatively easy for a person familiar with AL to write, and are generally at least partially self-documenting. Typically, a user wishing to know what a given library routine does can find out merely by looking at a listing of the routine, which will (of course) be written in a clear, well structured style with many comments describing the more obscure passages. Generally, such libraries are most useful where there is essentially only one way to do a given subtask, all actions required to do each subtask can be performed at one place in the output program, and different subtasks are essentially independent. When these conditions are not fully met, more powerful techniques are needed.

4.3 MORE POWERFUL PRIMITIVES -- AN OVERVIEW

Many domains are sufficiently complicated that macro expansion, even when used with conditional compilation, is too limited. In assembly, there may be a number of different ways to do some particular task; which way is "right" depends very largely on what other subtasks must be done. Similarly, it is frequently possible to perform part of one subtask (or, at least, to gather useful information) in the course of doing another one. Such considerations are in general very difficult to express within the paradigm of macro expansion.

In our introductory example, for instance, the system must decide how the engine block is to be oriented to facilitate putting on the head. Furthermore, the block alignment must be sufficiently well determined so that the the aligning studs can find their way into the holes. One way to do this might be to push the engine block up against a simple aligning jig consisting of a low wall. Other methods might include vision or simply grasping key features of the block and reading the hand coordinates. Once the head is on, the system must insert the bolts and drainplug. The system would like to avoid moving the engine block around more than it has to, since each move requires time and may introduce uncertainties. This means that it should choose a block position that allows the arm to reach the bolt and drain holes. If an aligning jig is in use, care should be taken to keep the side hole free if possible, and so forth. Furthermore, an alignment technique that visually locates the engine block head holes is apt to yield more useful information for the insertion tasks than would some cruder, but less expensive, test which may work just as well for the purpose of mating the head.

A full discussion of the mechanisms used by the system to transform a high level program into one that can actually run is beyond the scope of this paper. Briefly, AL works by progressive refinement of the user's program specifications, and uses process instantiation and communication mechanisms to keep track of the various **subtasks** and to ensure that all decisions are mutually compatible. Knowledge about assembly primitives is encoded into a number of procedures inside the expander. With each program statement, the system associates a process instantiation of the appropriate procedure (of course, the processes for low-level AL statements are fairly trivial). These processes are then arranged into a prerequisite graph based initially on the user's specification of what must be done before what (see subsection 2.5.3). A number of other "bureaucrat" processes are created to work out compromises, invent new service tasks, decide relative ordering, watch out for obvious inefficiencies (such as putting down a tool and then picking it right back up again), and so on. As the plan becomes more detailed, and as decisions are made about the order in which **subtasks** are to be performed, successive copies of the program graph are generated. (Additional information is stored both in the data base and in the internal state of the various **subtask** processes.) The final phase is to run down the (linearized) graph, asking each **subtask** process to generate the appropriate output code.

4.4 CALLING HIGH LEVEL PRIMITIVES

The syntax for high level primitives is keyword-oriented and resembles that for MOVE and OPERATE statements in the sense that there is a main clause naming the operation, with possibly a number of subordinate clauses giving further specifications as to what is to be done. For example,

```
INSERT screw 1 INTO hotel     (main clause)
    USING TOOL nutdriver      (subordinate clause)
    WITH TORQUE = 10          (subordinate clause)
```

For convenience and readability, a number of different forms are acceptable. For instance, the

words "WITH" and "USING" are interchangeable, and punctuation (like the "=", above) is frequently optional. Some of the subordinate clauses may themselves contain several elements, as in

```
FIT carburetor ONTO engine-assembly-1
    WITH ALIGNMENT
        carburetor-hole 1 OVER stud 1,
        carburetor-hole2 OVER stud2;
```

In such cases, a comma is used to delimit successive elements.

Initially, only a fairly small set of high level primitives is being implemented, although some (like INSERT) may be quite flexible. Even a few primitives, however, turn out to be sufficient for many interesting tasks, and provide quite a rich environment for investigation of how the various parts of the system interact.

Probably the most elaborate primitive is INSERT, which is generally responsible for insertion of shafts and shaft-like objects (including screws) into holes. The main clause is

```
INSERT <shaft-specification> INTO <hole-specification>
```

where the <shaft-specification> should be either an object of type shaft or one end of an object of type shaft. In the former case, the system will assume that the "bottom end" of the specified shaft should be inserted into the named hole. (See Section 4.7) Similarly, the <hole specification> may be either the name of a hole or of a bore, in which case the top end will be assumed. AL can learn a good part of exactly what it is being asked to do by looking at the object models. For instance, if the shaft and bore are both threaded and have the same diameter, then the system will attempt to screw in the shaft properly. Similarly, by looking at the chamfer of the hole, the taper of the shaft, and the region around the hole, the system can decide how much determination is required, what sort of search might be applicable, etc. Further specifications may be included in subordinate clauses, such as the TOOL and TORQUE clauses in our first example, or as in the TWIST clause of

```
INSERT aligning-pin INTO guide-hole
    WITH TWIST = 3
```

which says that the pin is to be given three turns counter-clockwise as it is pushed into the guide hole. Additional "advice" may also be provided in the data base. For instance, if there is a special routine for grasping "type 1" screws with the nutdriver, there might be an assertion of the form:

```
FOR M(GRASPING_METHOD, screwtype 1, nutdriver, routineid)
```

(This example rather oversimplifies the actual mechanism used to describe this sort of thing; a fuller description, however, is beyond the scope of this paper.)

Another fairly elaborate primitive is

```
FIT <object 1> ONTO <object2>
```

where <object 1> is usually a subpart of assembly <object2>. (See Section 4.7 for more details about assemblies.) If this is not the case, then the attachment location must be specified by a clause of the form

AT <transform>

The most common modifying clause for this primitive is an alignment specification, such as

WITH ALIGNMENT
<hole> OVER <shaft>,
<obj 1 feature> MEETS <obj 2 feature>,
<shaft> INTO <hole>

Other primitives include:

SLIP <collar> OVER <shaft> (includes nut over threaded shaft)

PLACE <object> ON <surface>
IN POSITION <stable position> {optional)

GRASP <object> AT <trans or frame>

TIGHTEN <bolt or nut>
WITH TORQUE <number> (this clause is required)

EXTRACT <shaft> (the inverse of INSERT]

4.5 WORLD MODELLING OVERVIEW

The planning information required by the very high level primitives is essentially a superset of that required for the basic manipulation control statements; the same underlying mechanisms are used, although sometimes in slightly different ways. This includes information about variable semantics, object shape and structure, error estimates, and the purposes of programs, in addition to the simple planning values and attachment structures used for low-level trajectory planning.

The expander frequently needs to consider the effects of some hypothetical action on a number of program steps. Similarly, it is often necessary to consider the effects of modifying some earlier decision or to find a way to perform some preparatory action at an early point in a program. AL handles provides for this sort of consideration by the use of a simple "multi-world" data base. Essentially, all fluent information (such as planning values of variables, assertions, etc) is associated with a set of "world" states for which it is true. With every program statement, AL then associates an "input world", which contains the planning model of the environment just

before the statement gets executed, and an "output world" which will reflect the expected effects of the statement on the runtime world. Normally, these two "worlds" can be the same when only low-level AL statements are involved, since such statements don't usually need to generate forward or backward references to other planning states.

Although multiple worlds are primarily intended for use by the expander, a user can make explicit references to different worlds by using

IN <worldname>

in ASSERT and DENY statements and in the various PLAN constructs. The plan-time atoms IWORLD and OWORLD always contain AL's internal names for the current input and output worlds, respectively. For example,

```
ATOM w;
s ←← 1;
w←← (IWORLD);
.
PLAN IF (*(s)= 1) IN *(w) THEN
        s ←← 2;
Comment, now *(s)=2;
```

-Note: IN acts syntactically like a very high priority boolean binary operator, so that

+(a)= 1 IN *(w1) v *(b)= I A *(a)=2 IN *(w2)

is equivalent to

(*(a)= 1 IN *(w1)) v ((*(b)=1 IN *(IWORLD) A (*(a)=2 IN *(w2))

4.6 INFORMATION ABOUT VARIABLES

The system must deal with a number of different sorts of information about variables and variable values. These include:

(1) *Metaphysical value.* The metaphysical value of a variable is that quantity which the variable is supposed to represent. Traditionally, knowledge about the meaning of variables has been more or less the exclusive province of the programmer. For example, low level AL constructs don't usually know or care what some user-declared frame variable really represents, although the system does understand a few predeclared variables (e.g., YELLOW, which gives the location of the yellow arm). On the other hand, a statement like "fit the pumphead onto the pump assembly" requires AL to "know" what variables represent object locations, mateing position, grasping positions, and so forth.

(2) Runtime Value. This is the value that a given variable will have at run time. The compiler has a name for it, and must generate code that references the corresponding memory location(s).

(3) Locus information. Crudely put, the locus of a variable is the set of possible runtime values for that variable. The term is also used here to mean the compiler's estimate of the locus. This estimate may merely be the planning value, or it may include a region bounded by constraints. These constraints may be expressed explicitly, as mathematical relations involving degrees of freedom, or implicitly, as semantic information like "the object is up against the wall."

(4) Determination information. The determination of a variable is essentially a compile-time estimate of how accurately a runtime value will reflect the corresponding metaphysical value. As with the locus, this information may be expressed in a number of ways.

For example, suppose we we want to compile code to pick up an object which we know will be sitting upright on the station. In such a case, the object will be free to rotate about the station z-axis and will be free to move in the station x-axis and y-axis directions. If we assume that the station is 15 inches square, this might be translated by the system into something like:

```
ASSERT FORM (LOCUS,obj,
     EXPRESSION( FRAME( ROT(Z,theta),VECTOR(xdf,ydf,0)) ));

ASSERT xdf ≥ 0*INCHES; ASSERT xdf≤15*INCHES;
ASSERT ydf ≥ 0*INCHES; ASSERT ydf≤15*INCHES;
ASSERT theta ≥ -π*RAD; ASSERT theta ≤ π*RAD;
```

where "obj" is a FRAME variable giving the location of the object, and "xdf","ydf", and "theta" represent the degrees of freedom.

Of course, there may be additional constraints on where the object is. For instance, suppose that the object is round and is known to have been shoved up against a low wall running diagonally across the station. This might give us a constraint like:

```
ASSERT xdf+ydf= 15*INCHES;
```

so that the object locus is now given by

```
FRAME(ROT(Z,theta),VECTOR(xdf,ydf,0))                    [Eq. 4.1]
0≤xdf≤ 10
Orydfr 10
xdf+ydf= 15
-π*RAD≤theta≤π*RAD
```

If the object had a flat side known to be shoved up against the wall, then we could also pin down theta to some fixed value, such as

```
theta ←← 0.75*π*RAD
```

Suppose that we now call a vision routine to locate the object to within one centimeter and three degrees. The vision routine will store some value, say

```
FRAME(ROT(Z,90),VECTOR(10,5,0))
```

into the value cell for obj. We clearly cannot know in advance that this will be that value returned, so the locus estimate given by Equation 4.1 will remain unchanged. On the other hand, the determination of obj has been improved to the point where the object can be picked up. In other words, if we execute the statement

```
MOVE YELLOW TO obj*objgrasp
```

then we know that the yellow arm will wind up sufficiently close to the nominal grasping point for the object for the picking-up operation to succeed. In planning a trajectory to do this, the system. will use its nominal value for obj, which (in the absence of any better advice) will be chosen at the center of the locus,

```
FRAME(NILROT,VECTOR(7.5,7.5,0) )
```

and then modified at runtime in the usual way.

This trajectory modification may cause problems if the runtime value of obj gets too far from the nominal value. To avoid this, the expander will ask the trajectory calculator to evaluate the suitability of its trajectory for extreme points of the locus of obj. If the modification seems to be too great, then the expander will ask for several trajectories to be planned and will generate conditional tests to select the correct one. We are currently investigating ways to facilitate this communication between the expander and the trajectory calculator. One very simple, though painstaking, method is to simulate moves to a number of spots. A better way would be for the trajectory calculator to generate constraints telling what regions a trajectory is good for, but it is a bit too early yet to tell how feasible this will be. Similarly, we are investigating ways for using runtime errors to determine when splitting of a region may be needed.

4.7 OBJECT DESCRIPTION

This section is intended to provide an overview of the sorts of information about objects that AL uses and of how this information is currently specified. It is not intended to be a complete list of *all* the assertions currently used or as a user's manual for building object descriptions.

Our primary interest so far has been to investigate ways to use descriptive information about objects, rather than to provide an extremely elegant input language for the descriptions. This has led us to specify explicitly a number of things which are, in principle, computable from a more general shape description. We expect that the process of describing an object to AL, which is

currently almost completely manual, will eventually become very largely automated, with most of the information being either directly available or computed from the output of computer-aided-design programs.

Currently, objects are described by assertions about their "interesting" properties. These assertions follow a number of conventions, so that the various high level primitives can use the information, although a user can, of course manipulate it explicitly. Shape is treated simply as another object attribute, and a several different shape descriptions may be present for a given object.

4.7.1 ONE -PIECE OBJECTS

Objects are represented as tree-like structures; typically, the "root" node contains information about the object as a whole, with "leaf" nodes telling about interesting features. By convention, we use a frame variable for the object name. (This variable is then assumed to give the object local ion).

For example,

```
FRAME valvebody,bore1,bore2,bore3;
PLANNING TRANS upright,upside_down;
PLANE topsurface;

upright ←← NILTRANS;
upside-down ←← TRANS(ROT(Y,π*RAD),VECTOR(0,0,1.8));

ASSERT FORM(TYPE,valvebody,OBJECT);
ASSERT FORM(GEOMED,valvebody,"valve.b3d");

ASSERT FORM(SUBPART,valvebody,bore1);
ASSERT FORM(SUBPART,valvebody,bore2);
ASSERT FORM(SUBPART,valvebody,bore3);
ASSERT FORM(SURFACE,valvebody,topsurface );

ASSERT FORM(STABLE_POSITION,valvebody,*(upright));
ASSER-T FORM(STABLE_POSITION,valvebody,*(upside_down));


ATTACH bore1 TO valvebody AT TRANS(NILROT,VECTOR(-1,0,2)) RIGIDLY;
ATTACH bore2 TO valvebody AT TRANS(NILROT,VECTOR(1,0,2)) RIGIDLY;
ATTACH bore3 TO valvebody AT TRANS(NILROT,VECTOR(1,0,3)) RIGIDLY;
```

declares that "valvebody" is an object whose GEOMED description is given by file "valve.b3d". There are three interesting "subparts", called "bore1", "bore2", and "bore3" and located at FRAME(NILROT,VECTOR(-1,0,2)), FRAME(NILROT,VECTOR(1,0,2)), and FRAME(NILROT,VECTOR(1,0,3)), respectively. Also, there is a planar surface called "topsurface" located at PLANE(1.8*Z,Z) in body coordinates. The valvebody can sit on the station in two "stable positions", upright and upside-down. Then, the assertion

ASSERT FORM(valvebody,ON_SURFACE,station,*(upside_down))

tells the system that the location of the valve body will be given by an expression of the form:

TRANS(ROT(Z,theta),VECTOR(a,b,0))*(upside_down)*station

For degrees of freedom theta, a, and b. This reduces to

FRAME(ROT(Z,theta'),VECTOR(a',b',1.8));

where theta',a',& b' are another set of free scalar variables.

The subparts, "bore 1", "bore2", and "bore3" are further described by assertions of the form:

```
ASSERT FORM(TYPE,bore1,BORE);
ASSERT FORM(DIAMETER,bore1,0.9);
ASSERT FORM(THREAD,bore1,32);
ASSERT FORM(LENGTH,bore1,0.30);
ASSERT FORM(TOP_END,bore1,hole1);
ASSERT FORM(BOTTOM_END,bore1,OPEN);

ASSERT FORM(TYPE,hole1,HOLE);
ASSERT FORM(LIES_IN,hole1,topsurface);
ASSERT FORM(CHAMFER_DEPTH,hole1,0);
ASSERT FORM(CHAMFER_WIDTH,hole1,0);
ASSERT FORM(LIP_SIZE,hole1,(3/ 16));

    (et cetera]
```

Here the system recognizes the word "BORE" as saying that bore1 is a negative cylinder (such as might result from a drilling operation). The attributes DIAMETER, THREAD, and LENGTH are obvious. TOP_END and BOTTOM-END, however, may require a bit more explanation. The "top end" of a bore is always a hole -- ie, an intersection between the bore and the object surface. If the bore completely pierces the object, then the bottom end will be also be a hole. Otherwise, it may be "OPEN" (which means that it opens into some uninteresting cavity inside the object, "CLOSED" (which means that it comes to an abrupt, but otherwise uninteresting, end), or a named surface (which usually only happens for relatively large holes), See Figure 4.1.

Frequently, a user wishes to declare a number of instances of a single prototype. This may be done by making assertions of the form:

ASSERT FORM(TYPE,<object>,<prototype>) .

For instance,

```
ASSERT FORM(TYPE,s1,screwtype1);
ASSERT FORM(TYPE,s2,screwtype1);
```

would declare s1 and s2 to be instances of screwtypel, where screwtypel might be specified by

```
ASSERT FORM(TYPE,screwtype1,SHAFT);
ASSERT FORM(DIAMETER,screwtype1,0.62);
ASSERT FORM(LENGTH,screwtype1,2.44);
ASSERT FORM(THREAD,screwtype1,28);
ASSERT FORM(TOP_END,screwtype1,headtype1);
ASSERT FORM(BOTTOM_END,screwtype1,tiptype1);

ASSERT FORM(TYPE,headtype1,CYL_HEAD);
ASSERT FORM(SLOT,headtype1,HEX 0.53);

ASSERT FORM(TYPE,tiptype1,FLAT_END);
```

Note that shafts also are considered to be directed and to have two ends. By convention, all screws, bolts, or similar objects are assumed to have- their heads at the **"top"** end. See Figure 4.2.

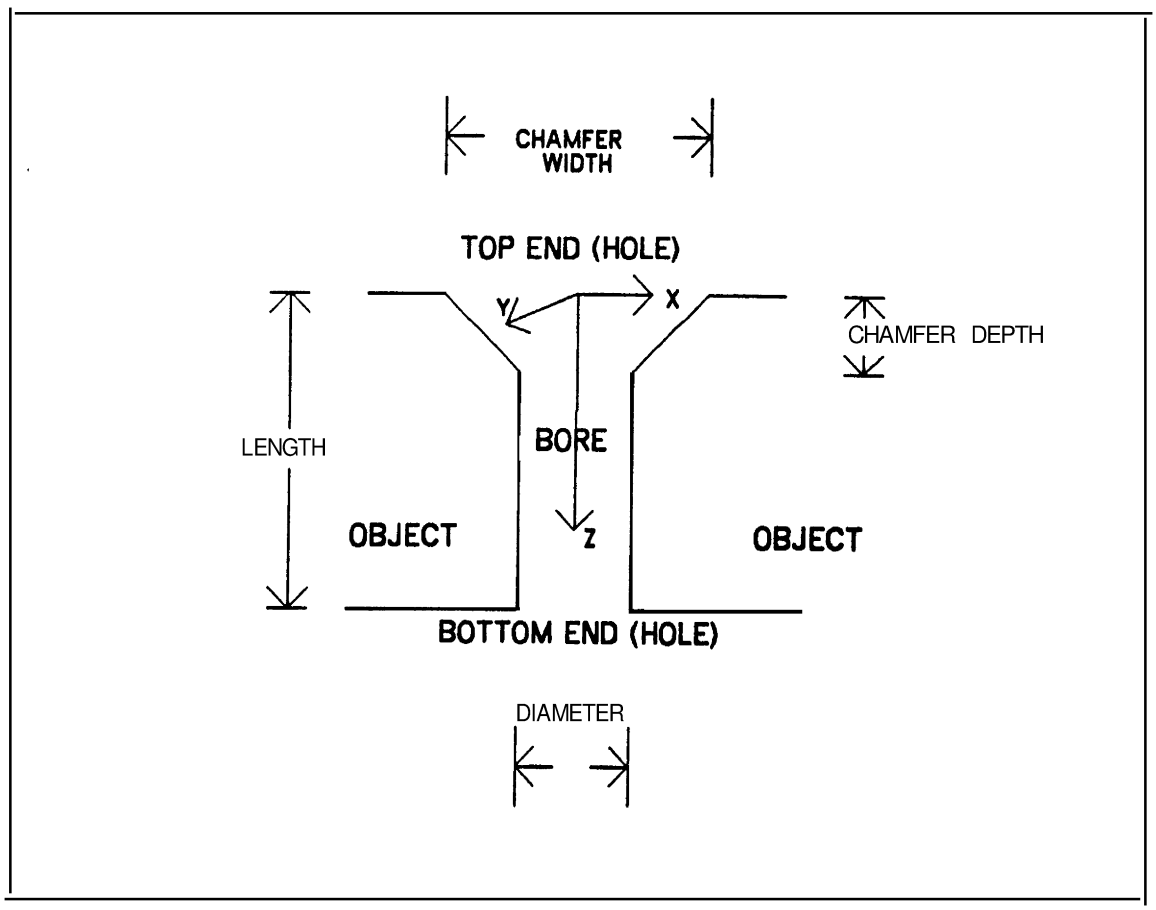

Figure 4.1
Bores and Holes

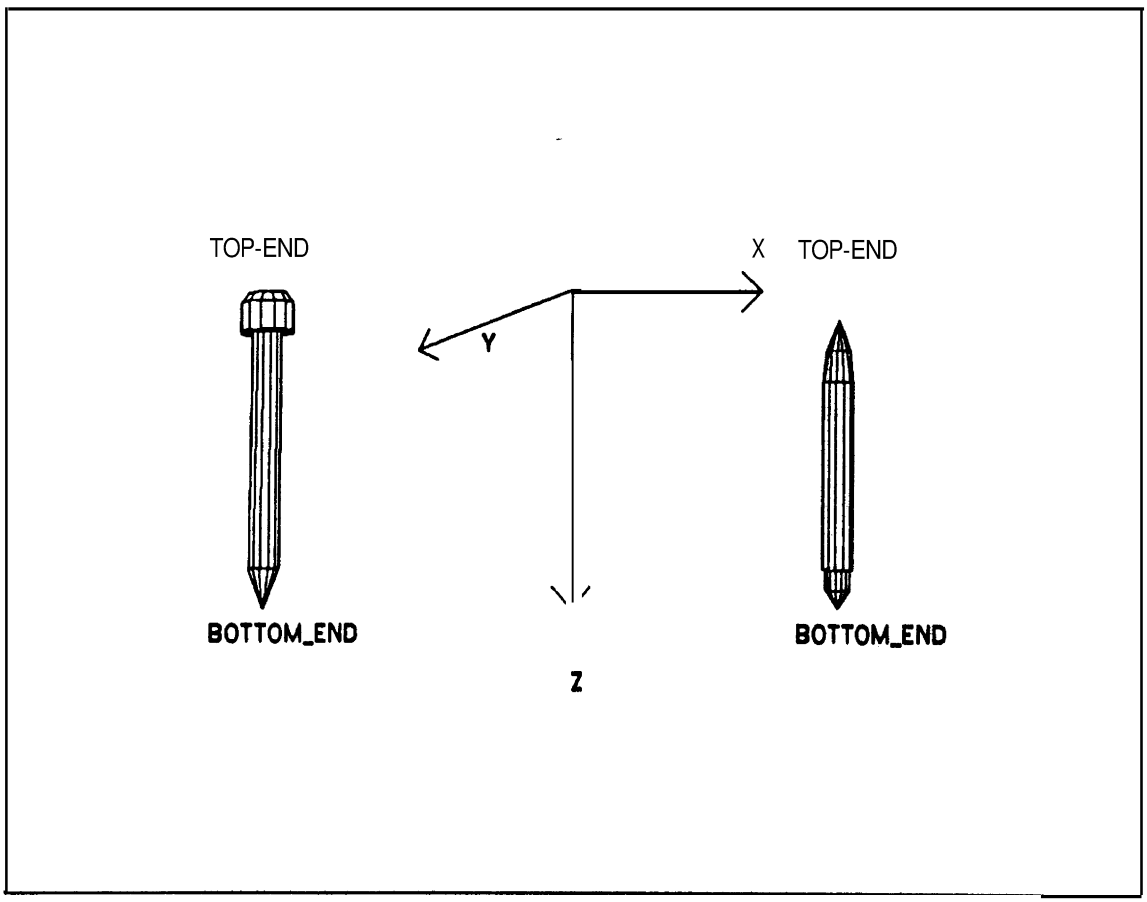

Figure 4.2
Shafts

4.7.2 ASSEMBLIES

An "assembly" is an object whose various subparts are removable.

For instance,

```
ASSERT FORM(TYPE,waterpump,ASSEMBLY);
ASSERT FORM(SUBPART,waterpump,gasket);
ASSERT FORM(SUBPART,waterpump,head);
ASSERT FOR M(SUBPART,waterpump,pumpbase);
.
ASSERT FORM(gasket,FITS,ONTO,waterpump,
          AT,TRANS(NILROT,VECTOR(0,0,3)));
.
```

Such objects provide a convenient framework for assembly tasks. Typically, one of the subparts is chosen as a "base part", which is used as an anchor to which the remaining parts are added.

In addition to the usual sorts of object attributes and the locations of the various subparts, assemblies usually contain a number of "semantic" assertions about how things go together. Some of this information is inherent in the design. For instance,

```
ASSERT FORM(DESIGNED_TORQUE,screw1,40)
```

Other 'information comes from the geometry of the parts, and (as indicated earlier) could theoretically be computed from the shape description but is of enough interest to be worth representing directly, especially in cases where the computation required is non-trivial. For example,

```
ASSERT FORM(MATED,pumpbase.top_surf,gasket.bottom_surf)
ASSERT FORM(ALIGNED,head.bore1,gasket.bore1,pumpbase.bore1)
ASSERT FORM(RUNS_THRU,s1,gasket.bore1;
ASSERT FORM(RUNS_THRU,s1,head.bore1);
ASSERT FORM(SCREWED_INTO,s1,pumpbase.bore1);
```

4.8 EXAMPLE: WATERPUMP ASSEMBLY PROGRAM

This short example is intended to give some feel for what a very high level program for a simple task looks like.

The task here is to mate the pump head and gasket with the pump base using two aligning pins,

then to secure the head with six machine screws. This task requires only a few basic operations, the principle ones being FIT . . . ONTO and INSERT, and is very similar to one actually performed by WAVE at Stanford. The WAVE program for this task consists of about 450 lines of "machine language"-like code, and was written over a period of several weeks by Bob Bolles and Lou Paul. (Most of this time was spent on improving WAVE and developing techniques; more recent tasks of similar complexity have taken on the order of three to eight days) The same program, rewritten in low-level AL, would be somewhat shorter, although it would still require a fair amount of detailed effort on the part of the programmer.

```
pump: BEGIN

REQUIRE "PUMP.075" SOURCE-FILE;
```

(This file would contain many assertions describing the pump assembly and all its subparts. Eventually, such descriptions will most likely be produced as part of the output of design automation programs. See the section on object descriptions for a sampling of the sorts of things one might see here.}

```
REQUIRE "STATN.04" SOURCEJILE;
```

(Reads in description of the work station. This would include location of tool racks, standard "jigs" that may be available, etc.)

```
ASSERT FORM(pumpbase,ON_SURFACE,conveyor_belt,*(upright));
```

(This assertion tells the strategist the initial location & "stable position" (ie "upright") of the pumpbase. The value of "upright" is assumed to be set up in "PUMP.075".
The dynamic frame "conveyor-belt" is assumed to have been defined in "STA TN.04".
A ctually, such moving devices won't be handled by early versions of AL. A n alternative would be to arrange the pumpbases in an array to one side of the work station (perhaps using an "egg carton" arrangement to make it easier to pick one out).)

```
ASSERT FORM(pumphead,ON_SURFACE,side_table,*(onside));
```

{A number of other assertions 'might go here.)

(Here, we will use TASK BEGINs and allow the system to decide on the relative order of the various subtasks.)

```
aligning: TASK BEGIN

    INSERT pin 1 INTO pumpbase.hole 1;
    INSERT pin 1 INTO pumpbase.hole2

  END aligning;
```

(Note Acre that we are allowing the system to decide how it will locate the pumpbase and whether it will leave it on tie conveyor belt throughout the assembly or place it in some temporary work area. Of course, we could have made these decisions explicitly. For instance,

```
PLACE pumpbase ON station
      IN POSITION upright
      WITH ALIGNMENT left_side AGAINST wall1,
                     back-end AGAINST wall2;
```

could have been the first statement of the program.
"wall1" & "wall2" are low wails described in "STATN.04" and form a corner which could be used as a simple jig. "left_side" & "back_end" here would be defined in "PUMP.075" as components in the "footprint" of the pumpbase. See the section on object description for further details.)

```
FIT gasket ONTO pumpbase,assembly
    WITH ALIGNMENT gasket.hole1 OVER pin1,
                   gasket.hole2 OVER pin2;
```

{The system uses its object model for the pumpbase assembly to tell it how the gasket fits onto the pumpbase.}

```
FIT pumphead ONTO pumpbase,assembly
    WITH ALIGNMENT head.hole1 OVER pin1,
                   head.hole2 OVER pin2;

boltdown: TASK BEGIN

s3op: INSERT s3 INTO head.hole3
          WITH TOOL driver1,
          WITH TORQUE hand-tight;
    END;

s4op: INSERT s4 INTO head.hole4
          WITH TOOL driver1,
          WITH TORQUE hand-tight;

s5op: INSERT s5 INTO head.hole5
          WITH TOOL driver1,
          WITH TORQUE hand-tight;
```

PLACE pump-assembly ON conveyor-belt IN POSITION upright;

{This will cause the system to pick an orientation for the completed pump assembly & put it on the conveyor. The system can, of course, "remember" the position it picks. *If there were some further task to be done on the pump, the system will know where to find it.}*

END pump;

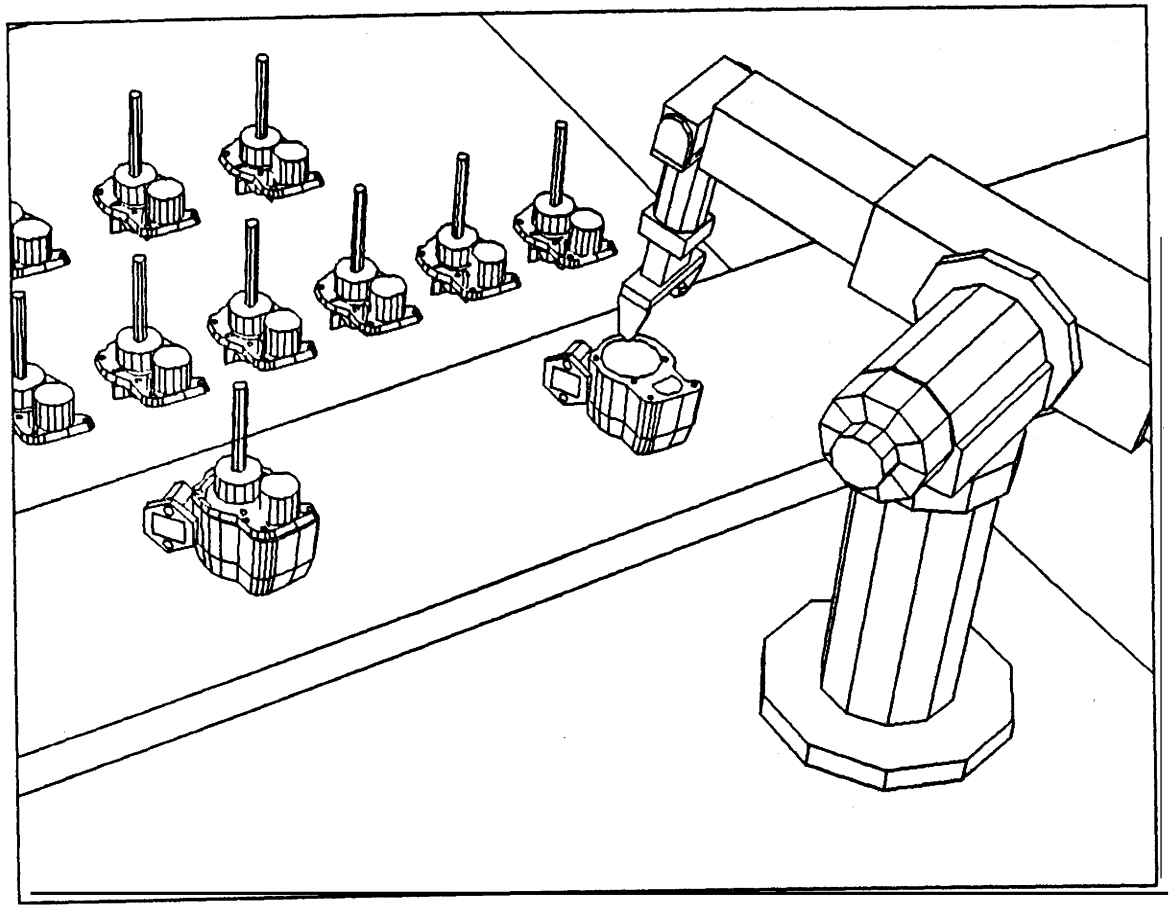

Figure 4.3
Pump Assembly Station

CHAPTER 5
RUNTIME OVERVIEW

The **runtime** is a set of programs residing in the PDP-11. We will discuss control structures and data structures.

5.1 CONTROL STRUCTURES

There are several types of processes any number of which can be active at any time:

1) Interpreters
2) Joint servos
3) Condition monitors

An interpreter is a process which is executing arithmetic or other stack-oriented instructions, not one of the moves. Most straightforward AL code is executed by interpreters. During execution of simultaneous blocks, or while the conclusion of a condition monitor is running, there can be more than one interpreter.

Each active interpreter has a stack on which it **places** operands, a program counter which points to its particular block of code, and a list of those condition monitors for which it is responsible. Each interpreter also has a reserved cell in which it stores information concerning its current location in the source code; this is useful for debugging. The code which it interprets includes instructions for stack manipulation, arithmetic operations, starting up subsidiary interpreters, flow of program control, and preparation for motions. As soon as a move is encountered, the active interpreter starts up the required joint servos and condition monitors and waits for the termination of the move before continuing.

A *joint servo* is a process whose task is to servo one joint of a moving device according to the planned trajectory for that joint. When finished, the servo stops the joint **and** disappears, If the motion should be stopped by some other process, the servo takes care of actually stopping the joint before it disappears. During its life, the servo is in charge of applying to one motor the correct current, which will change over time. The correct signal is calculated based on the planned location of the joint, its observed location and velocity, and its recent positional error, After emitting the proper drive, the servo precalculates as much as it can for some future time, when it will again modify the drive, and then waits for that future time to arrive.

A *condition monitor* is a process which continually checks for some condition. If that condition should appear, then those actions specified by the compiler as critical are done immediately (in a non-interruptible fashion); for the rest, the monitor starts up an interpreter. The condition monitor can be in two states: enabled and disabled. The checking is only 'done while the monitor is enabled. A monitor disappears only when the system kills it. An enabled condition monitor can be of two types: hardware or software. The hardware type is a true interrupt handler that can

react to some hardware condition. An example of this is a monitor to detect something hitting the touch pads on the fingers. The software type is a set of calculations which are to be repeated frequently, the result of which is a decision whether or not to trigger the conclusion of the monitor.

These various types of processes are scheduled by a combination of priority structure and **time-slot** request disciplines. Joint servos are critical in the sense that the calculations they make are highly time-dependent; they must be guaranteed not to be interrupted. Therefore, they operate at a very high software priority. Condition monitors are **less** critical, and they operate at a lower priority. Interpreters run at the lowest priority. Both joint servos and condition monitors are tasks which need to be awakened periodically. Therefore, time is divided into slots one millisecond wide. One servo and any number of condition monitors can reserve a time slot; when that time arrives, the servo is given guaranteed control, and when it terminates, all requesting condition monitors are allowed to use the time remaining in the slot. After all these critical requests are satisfied, any running interpreter **uses** the time left over until the next slot begins. Appendix 5 describes the instructions available to the interpreter, the tables emitted for motions, the nature of joint servos, and the priority interrupt and scheduling structure in greater detail.

5.2 DATA STRUCTURES

5.2.1 VALUE CELLS

Values are stored in cells; each **datatype** has its own format for the value cell. Floating point numbers are used throughout. Dimensions (like time, distance) are not kept at **runtime;** they are purely for use in the compiler to make consistency checks.

Scalars are stored as a single, floating point word.

Vectors are stored in four consecutive words. The fourth entry is usually 1; the arithmetic routines are optimized for such normalized vectors. To normalize a vector, divide each entry by the fourth one.

Planes are also stored in four words. The first three represent an outward-facing normal, and the last is the negative distance to the (table) origin.

Frames are stored as 4x4 arrays, by columns. In addition, there are 6 words set aside for the joint angles associated with the frame, that is, the angles necessary for one of the arms to reach that point in space. There are a few bits to tell which arm is meant and whether the joint angles are valid, that is, whether they have been calculated since last the frame's value was changed. Joint angles are calculated only if needed. This happens if the frame is being used as a point in *a* trajectory.

Transes are stored in two 4x4 arrays: One holds the trans itself, and the other its inverse.

5.2.2 GRAPH STRUCTURES

Variables are allocated "node cells". These cells have a pointer to the value cell, as well as other fields used in graph structure manipulation.

NODE CELL

invmark -- =0 if value is valid, otherwise invalid (note: the **evalnode** algorithm uses a "time" to detect cycles. Therefore, this field needs to be (at least) 16 bits.
value -- pointer to a value cell.
calculator -- points to a list of calculator cells
changer -- points to a block of interpretable code. There are a few special-purpose changers which do not point to any code, but are used as shorthands.
dependents -- points to a list of dependents
type -- encoding (in several bits) of datatype.

CALCULATOR CELL

link -- link to next on the chain (there can be more than one calculator for a node).
needed -- points to list of variables needed for this calculator. The dependents **cell** format is used for the needed list.
code -- points to a block of interpretable code.

DEPENDENTS CELL

link -- link to next on the chain (there can be more than one dependent of *a* node).
dep -- points to the node cell of one dependent.

The algorithms used to extract values from and insert values into the graph structure are described in Appendix III.

CHAPTER 6
EXTENSIONS TO AL

6.1 INCORPORATING VISUAL FEEDBACK

6.1.1 NECESSARY CAPABILITIES

This is a list of capabilities which would have to-be implemented in order to do dynamic visual feedback within AL.

PICTURE BUFFERS AND WINDOWS

We need a new datatype, PICTURE, to contain a digitized picture, information on the camera used (particularly its location and orientation), what lens was used, what filters, and perhaps other information.

Subpictures, that is windows, should be extractible from the picture itself, so that a visual processing routine can look at whatever part it needs.

CAMERA CONTROL

There should be a syntax for specifying how to move a camera to a desired location, For example,

```
AIM CAMERA-1 AT VECTOR(30,40,10)
     USING LENS=2, FILTER-CLEAR, IRIS=2.8;
```

There should be a syntax for specifying that a picture be taken and stored in a certain picture buffer. Since cameras have their own built-in synchronization, detailed timing control may be complicated. Read the *explicit control of timing* section below for some more ideas on this subject.

OBJECT MODELS

There should be sufficiently powerful data structures (such as arrays and list structures) available to implement complex object descriptions such as a network of features.

It should be possible to implement programs which find predicted objects in pictures by use of modeling information. This may involve the use of recursion and backup, neither of which is currently available.

VISUAL PROCESSING PRIMITIVES

There should be a mechanism for calling PDP11 and SPS41 routines which share data such as pictures and object models. (The SPS41 is a signal processor which we will use for some vision work.) To an extent, this already exists with the EXTERNAL MINI procedure.

MOTIONS OF ACCOMMODATION

There should be a way of specifying how to servo an arm based upon visual, force, or tactile information. The arm is expected to change its trajectory as a function of sensory input; this would allow visual servoing, for example. An implementation would involve dynamically changing the arm's destination or dynamically specifying relative changes to be made. In either case, time is an important variable. Consider a typical sequence of events:

(1) A picture is taken of the arm.
(2) The picture is analyzed to determine an arm correction.
(3) While the visual processing is being done, the arm continues to move. Hence a prediction should be made and incorporated into the specified correction.
(4) The correction is sent to the servo.

EXPLICIT CONTROL OF TIMING

As pointed out above, time is an important factor within visual feedback. It will be necessary to have "picture ready" events which occur when data are ready for processing; it might be desirable to allow explicit timing and scheduling to make efficient use of the camera.

It would also be useful to separate the 'setup' for a MOVE from the actual beginning of a move. This suggests a setup and trigger mechanism to squeeze as much processing as possible into "free" PDP 11 time.

INTERACTIVE DESIGN OF VISUAL PROCESSING

There should be an interface to a graphics system such as Bruce Baumgart's GEOMED [Baumgart] so the user can symbolically position the assembly parts and cameras, simulate arm motions, and extract potential object models from synthetic pictures. The system supervisor should be flexible enough to allow the user to interactively manipulate the actual arms and cameras so that the resulting TV pictures correspond with the synthetic views. This involves consistent models of the world.

6.1.2 STAGES IN INCORPORATING VISUAL FEEDBACK

There are roughly three different stages in the process of incorporating visual feedback into AL: (1) completely separate modules, (2) picture taking within AL but models and processing separate, and (3) everything in AL. These stages are briefly discussed below.

COMPLETELY SEPARATE MODULES

This means that the object modules, interpreters, camera control routines, etc. are in one or more modules and the AL system is another module. Communication between modules is by messages. This type of communication restricts the mode of operation; feedback will only be available while the arm is not in motion. Motions of accommodation would not be possible.

The current Stanford hand-eye system is of this form. It will be straightforward to provide this type of system with AL. However, it has obvious limitations and hopefully would only be a temporary solution.

PICTURE TAKING WITHIN AL

This is the first step toward a complete integration. AL would provide camera control, pictures, picture taking, and ways to call procedures which share data. The object models could either be written in SAIL (and be on the PDP 10) of be written in a PDP11 language (and be on the PDP 11). In either case the models and pictures would be available to external routines which analyze pictures and return improved location values for objects. Visual servoing and dynamic feedback still could not be done; there is no way to control the scheduling to insure the necessary service.

This type of procedure-calling is designed into the current AL system. It mainly involves a smart loader. The other extensions are reasonably straightforward; it appears to be an easy step up to this type of system. Its advantage over the previous system is that the basic requirements for doing visual feedback are all directly accessible from within one system (assuming the routines are on the PDP 11). This provides a chance to try out some of the ideas before moving on to the next stage.

COMPLETE INTEGRATION

Complete integration would involve motions of accommodation in full generality, with modifications to trajectories while they are being executed. Picture taking and processing would all be run under AL, and they would be interfaced into the timing scheme to insure proper service. Not only would true visual servoing be possible, but also fine control of the hand based on delicate touch sensing.

6.2 DYNAMIC FRAMES

One very desirable feature would be an ability to describe and use continually varying variables, In industrial applications, for instance, the runtime system should automatically make the corrections required to track an object on a moving conveyor. Initially, this facility is not being implemented, although we are studying the problems involved. Actually, only a very few new constructs would need to be introduced into the language to allow such things to be described. The principal addition required is a way of warning the compiler that some variables may be *dynamic*. For instance,

```
DYNAMIC DISTANCE VECTOR v;
DYNAMIC FRAME chain-hoist;
```

would tell the compiler that v and chain-hoist may vary continuously with time. Trajectories to any locations that depend on such variables must be handled a bit differently by the servo. Instead of applying the brakes at the end of a MOVE, the servo should periodically recompute the destination location, obtain a new arm solution, and then servo to the new joint values.

The normal AL graph structures are readily adapted to such dynamic values. Essentially all that is required is the addition of a special reserved scalar variable TIME, which is changed every clock tick, thus invalidating any values calculated by expressions that depend on TIME (see Section 2.4 and Appendix III). For instance we might have

```
DYNAMIC FRAME conveyor-belt;
VELOCITY SCALAR speed; [speed of the conveyor belt}
speed ←5*IN/SEC;

conveyor-belt <= FRAME(NILROT,speed*TIME*Y);

    {In this example, we won't ever use the "true" location of the belt. Rather, we
    will affix things to it, so that they are carried along by the belt.)

TIME SCALAR t0;
REQUIRE "PUMP.075" SOURCE-FILE;
    (This defines, among other things, the frames pumpbase and pumpgrasp.
    Initially, suppose that rue know that the pumpbase is somewhere on the conveyor.
    We call a vision routine to find it.)

VISUALLY_LOCATE(pumpbase,t0);
    (Also, set t0 to the value of TIME at which the Picture was taken (ie the time
    that the pumpbase was at the location set by the procedure).)

AFFIX pumpbase TO conveyor-belt
    AT (pumpbase → FRAME(NILROT,speed*t0*Y));

(One effect of this is:
      pumpbase(t) <= (pumpbase(t0)→conveyor_belt(t0))*conveyor_belt;
}

MOVE YELLOW TO pumpgrasp;

    (Presumably, pumpgrasp is attached rigidly to pumpbase. Since pumpbase is
    attached to a dynamic thing (conveyor_belt) then pumpgrasp is computed
    dynamically, too, so that the arm will track the grasp point.)

CENTER YELLOW;
 (grasps the object)
```

```
UNFIX pumpbase FROM conveyor-belt;
AFFIX pumpbase TO YELLOW;
MOVE pumpbase TO jig-location-1; {wherever that is}
```

It is perhaps worth pointing out that there is nothing particularly magical about TIME; a similar technique could be used, say, for moving to some frame whose value is a function of a continuously varying A-to-D reading.

6.3 EXTENSIONS TO OTHER ARMS AND DEVICES

The initial version of the 'AL system will be designed to run with two Stanford Arms, but the system is in no way limited to any particular manipulators, All manipulator-dependent routines are grouped together and are written in SAIL; in order to interface another manipulator to the system these routines would have to be rewritten, most notably the solution and dynamics models. In the case of non-manipulator type devices, such as cranes, the trajectory generating routines would also need rewriting, but as we lack any experience in this direction we will pursue it no further at this time.

Simple devices such as vices or tools have their own keyword syntax and are controlled by the OPERATE statement. In this case new routines would need to be added.

6.4 FINE CONTROL

Interactive control of the arm has to date been limited; we can output joint torque and monitor joint position, and have two binary touch sensors inside the fingers. Force-sensing elements are being developed for the hand and we are interested in more powerful touch sensors; when we have gained experience with these devices we will extend the language to facilitate their use. The present version of the language reflects those things which we have verified in practice and feel will move development in the right direction.

6.5 COLLISION AVOIDING

Since the available collision avoiders are quite slow, the initial system relies upon the user to provide his own collision avoiding in the form of VIAs and DEPROACHes. When fast collision avoiders become available they can be meaningfully included in the system.

CHAPTER 7
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APPENDIX I
EXAMPLE DIALOG WITH THE AL SYSTEM

Here is a sample conversation a user might have with AL. It demonstrates the following features: Typing in source code by hand, requesting source code to be read from a file, immediate execution of commands by the arm, return of values from the arm, loading compiled code into the runtime computer, and executing that code. The supervisor prompts with the sign "⊃". The material in the right-hand column is explanatory.

```
⊃ COMPILE TTY                                   | Request to read in from
                                                |   console for compilation,
c type <alt> when done ⊃                        | Message from supervisor
MOVE YELLOW                                     | Simple move statement
    TO FRAME(ROT(X,90),VECTOR(20,30,1));        |   Destination
FRAME PLACE1;                                   | Declaration
PLACE1 ← YELLOW;                                | Assignment
PLACE2 ← PLACE1 + VECTOR (0,0,5);               | Assignment
c OK to declare PLACE2 a FRAME? ⊃ YES           | Parser error, with option.
$                                               | End of file (altmode)
c no errors. compiled:  TTY(1) ⊃                | Compiler message.
                                                |
                                                | Now user wants to park arm,
⊃ COMPILE TTY                                   | Request to read in from
                                                |   console for compilation
c type <alt> when done ⊃                        | Message from supervisor
YELLOW ←← READ (YELLOW) ;                       | Get planning value of Yellow
                                                |   arm correct
ROVE YELLOW TO YPARK $                          | User wants to park the arm
c no errors. compiled:  TTY(2) ⊃                | Compiler message.
⊃ EXECUTE TTY(2)                                | Request to execute park
                                                |   code
c loading TTY(2) ⊃                              | First, loading to be done
c executing TTY(2) ⊃                            | Message as execution starter
c done ⊃                                        | Message at end of execution
                                                |
                                                | Now user wants to try his new
                                                |   code
⊃ EXECUTE TTY(1)                                | Request to execute code
c loading TTY(1) ⊃                              | First, loading to be done
c executing TTY(1) ⊃                            | Message as execution start8
c done ⊃                                        | Message at end of execution
                                                |
⊃ PLACE3 ←← READ(YELLOW)                        | Ask to read hand position
c OK to dec I are PLACE3 a FRAME? ⊃ YES          | Use of undeclared variable
⊃ WRITE(#(PLACE3))                              | Want planning value
c #(PLACE3) = FRAME(ROT(VECTOR(.3,.5,.82,17*DEG),
                  VECTOR(19.9*CM, 38.1*CM, 1.1*CM)) ⊃
                                                |   Indication of what was set
⊃ WRITE(PLACE4)                                 | Want runtime value
c PLACE4 not dec I ared ⊃                       | No runtime value!
⊃ WRITE(#(V1))                                  | Request for planning value
c #(V1) = VECTOR(3.0, 8, 28.13) ⊃
⊃ V1 ←← VECTOR(4.8, 8, 28.131                   | User can change planning
                                                |   values.
⊃ V1 ← (4.0, 8, 28.13)                          | User can change real values.
```

```
⊃ COMPILE HACK.AL[1,LOU]                    | Ask for compile from file
c Error in line 310 of HACK.AL[1,LOU].      | Parser error message
                          THEN              | Gives line with <lf>
                               STUP         |   at point of error
Option ⊃ ?                                  | User typed "?"
I:      Insert replacement text             | A list of options to user
z:      Use line editor to fix              |
II:     Show more context                   | This would give entire
F:      Flush to end of statement           |   statement
E:      Switch to E                         | E is a text editor
s:      Switch to SOS                       | SOS is a text editor
Q:      Quit. Abort compilation             |
Option ⊃ I                                  | User chooses to insert
                                            |   replacement
c type <alt> when done ⊃                    | Message from supervisor
                          THEN STOP         |  "STUP" changed to "STOP"
$                                           | End of insertion
c error in line 528 of HACK.AL[1,LOU].      | trajectory calculator error
                                            |   message
        MOVE YELLOW                         | Only first line of
                                            |   statement given
The desired motion goes out of bounds in joint 3
in the first segment of motion.             |
                                            | A bad motion
Option ⊃ E                                  | User wants to edit with E.
c Switching to E.  To return, <CTR>XRU<CR> ⊃|
                                            | Universe is saved for retry
c Welcome back to AL.                       | Editing done
Compilation of HACK.AL[1,LOU] aborted ⊃     | After an edit, compilation
                                            |   aborts,
⊃ COMPILE HACK.AL[1,LOU]                    | Request for recompilation
c No errors. Compiled: HACK.AL[1,LOU] ⊃     |
                                            | Compilation succeeds.
⊃ LOAD TTY(1),HACK.AL[1,LOU]                | Request to load into servo
c Loaded:  TTY(1), HACK.AL[1,LOU] ⊃         |
⊃ STATUS                                    | User wants to know where
                                            |   he is
Compiled: TTY(1),TTY(2),HACK.AL[1,LOU]      | Compilation status
Loaded: TTY(1), HACK.AL[1,LOU]              | Runtime status
⊃ EXECUTE                                   | Request for execution
c Executing TTY(1),HACK.AL[1,LOU] ⊃         |
⊃ STATUS                                    | User wants to know uhere
                                            |   she is
Interpreter at line 320 in HACK.AL[1,LOU]
                                            | Runtime status
c Interrupted by red button>                | Runtime error message. User
                                            |   interrupted motion.
Interpreter at line 180 of HACK.AL[1,LOU]
                                            | Servo status
⊃ PROCEEO                                   | Request to continue motion
c Joint 4 has excessive force.              | Runtime error message.
Interpreter at line 158 of HACK.AL[1,LOU]
                                            | Servo status
⊃ DELETE HACK. AL                           | Request to delete last
                                            |   compilation
c Deleting HACK.AL from runtime             | Removed from runtime
c Deleting HACK.AL from COMPILATION         | Removed from world of
                                            |   compiler
```

```
⊃ E                                          | Switch to E.
c Switching to E.  To return, <CTR>XRU<CR>⊃
c Welcome back to AL⊃                        |
⊃ COMPILE HACK.AL[1,LOU]                     | Request for compilation
c No errors, Compiled: HACK.AL[1,LOU] ⊃      | Compilation succeeds
⊃ SAVE WORLO IN W1                           | User wants world saved in
c World saved in W1.WLD ⊃                    |    named location.
⊃ RESTORE WORLD FROM W0                      | Request to restore Previous
                                             |    world
c W0.WLD not found ⊃                         | Expander error message
⊃ RESTORE WORLD FROM W80                     | Request to restore previous
                                             |    world
c done                                       |
⊃ BYE                                        | Request to leave the room
c Final status:                              | A final status rundown
Load modules ready:  TTY(1).HLD, TTY(2).HLD, HACK.HLD
Goodbye ⊃
EXIT
.
```

APPENDIX II
PROGRAMMING EXAMPLES

11.1 BOLTING A BRACKET ONTO A BEAM

This is intended to be a series of progressively more complex examples which demonstrate some of the features in AL, including affixment, control structures, macros, and library routines. The first set of the examples have essentially the same goal: bolt a bracket to a beam. Each example takes into account more possibilities or contains a different way of expressing the same thing.

The initial affixment structure is:

```
STATION
  YELLOW
  BLUE
BRACKET
  BRACKETHOLE
  BRACKET-GRASP
BOLT
BEAM
  BEAM_HOLE
```

The final affixment structure is:

```
STATION
  YELLOW
  BLUE
BEAM
  BEAM_HOLE
  BRACKET
    BRACKETHOLE
    BRACKET-GRASP
  BOLT
```

The initial structure can be created by the following declarations and assignments. See Figure 2.1.

```
FRAME beam, beam-hole;
FRAME bracket, bracket-hole, bracket-grasp;
FRAME bolt;

beam ← FRAME(ROT(Z, 90*DEG), VECTOR(30, 24.2, 0));
    (Beam is not affixed to anything initially  Thus its default DEPROACH is the station's
    DEPROACH which is: TRANS(NILROT, 10*CM*Z))
```

beam-hole ← beam * FRAME(ROT(X, -90*DEG), VECTOR(5.1, 0, 15));
{*FRAME(ROT(X,-90*DEG), VECTOR(5.1, 0, 15)) is the relative transform from beam to the beam-hole. Another way of looking at this is that within the beam's frame of reference, the beam-hole is at FRAME(ROT(X, -90*DEG), VECTOR(5.1, 0, 15)) The premultiplication by beam transforms this relative location out to the corresponding position (in station coordinates) with respect to the current location of beam.)*

AFFIX beam-hole TO beam;
ASSERT FORM(DEPROACH, beam-hole, TRANS(NILROT, VECTOR(0, 0, -3));
{*this sets up a DEPR OACH of -3 centimeters in the Z direction of the beam_hole's coordinate system.)*

bracket ← FRAME(ROT(Z,90*DEG), VECTOR(20, 40, 0));
bracket-hole ← bracket * FRAME(ROT(X,180*DEG), VECTOR(5.1, 2, 0));
AFFIX bracket-hole TO bracket;
bracket_grasp ← bracket * FRAME(ROT(X, 180*DEG), VECTOR(0, 1.5, 5));

AFFIX bracket-grasp TO bracket RIGIDLY;
(Notice that changing bracket-grasp will automatically change bracket, which in turn will automatically change bracket-hole. This is very handy if the position of the whole 'object' is being updated by one grasping position (ie. bracket-grasp.)
bolt ← FRAME(ROT(Z,90*DEG)*ROT(X,180*DEG), VECTOR(30, 60, 5));
{*The bolt is assumed to be sticking out of a dispenser.)*

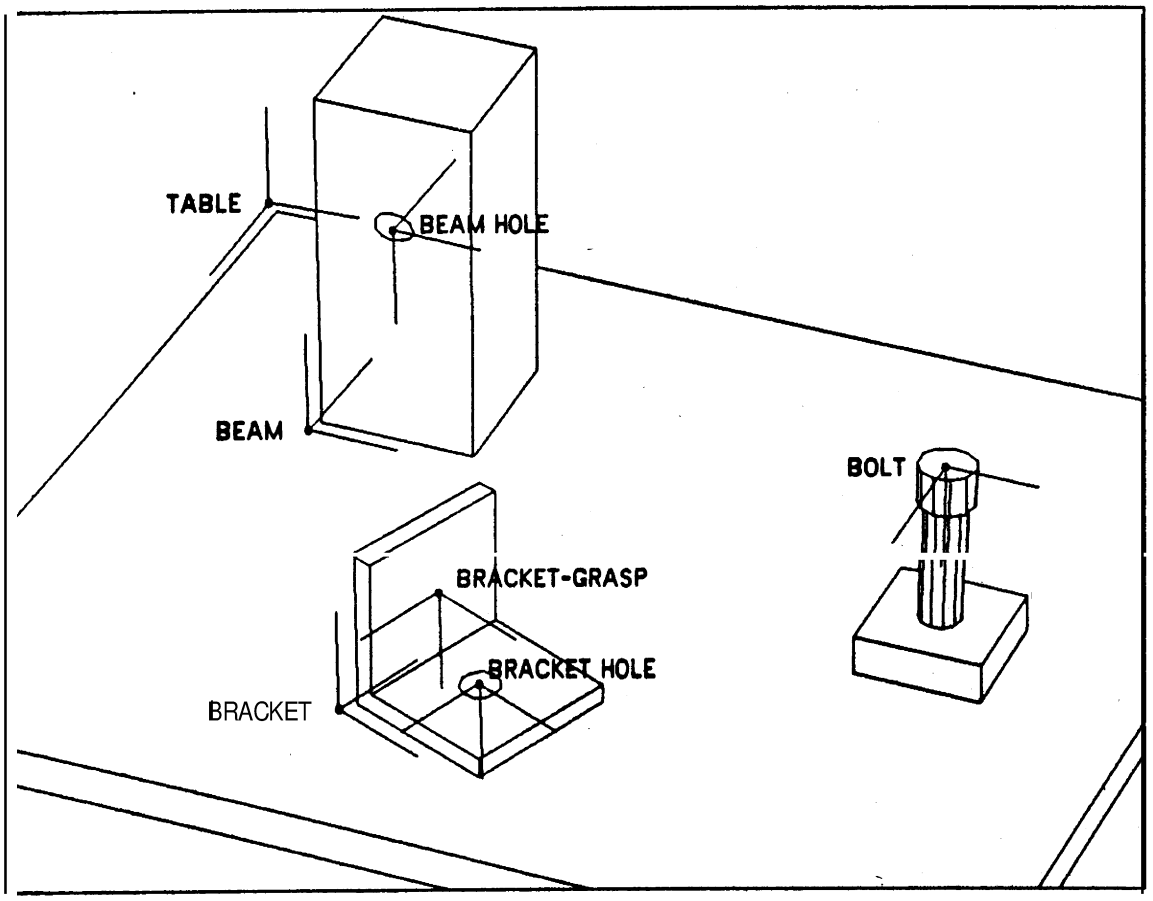

Figure 2.1
Initial World

11.1.1 EXAMPLE ONE

The task involves the following steps:

(1) Pick up the bracket with the YELLOW arm and position it next to the beam so that the holes line up.

(2) Pick up the bolt with the BLUE arm and insert it in the hole (in this example it is not screwed in; a later.example will use a socket driver to tighten the bolt).

(3) Return both arms to park.

The bracket is assumed to be 1 cm thick , and the bolt 4 cm long. The following program is a straightforward way to express the motions and feedback necessary to carry out the task. Everything is assumed to be in the right place and every motion is assumed to accomplish its desired effect. For example, this program assumes that the arm is accurate enough to align the bracket-hole with the beam-hole and to insert the bolt without hitting the side or binding. Later examples will take this type of error into account.

```
DEFINE OZ = "72.007789*DYNES";
    (This macro defines a unit of force OZ equal to 1/16 poundal}

OPERATE YFINGERS WITH OPENING=3*CM;
MOVE YELLOW TO bracket-grasp;
    (Since bracket-grasp does not have a DEPROACH explicitly associated with it, the
    compiler checks to see if it is affixed to anything. It is: bracket. But bracket does not
    have a DEPROACH associated with it either. Is it affixed to anything? No. Therefore,
    by default the compiler uses the STATION's DEPROACH (ie.
    TRANS(NILROT,10*CM*Z)) as the approach for bracket-grasp.)

CENTER YELLOW;
    (This closes the fingers until they grab something.)
bracket-grasp ← YELLOW;
    (Since bracket-grasp is RIGIDLY affixed to bracket, this statement updates bracket and
    hence anything affixed to bracket (eg. bracket_hole). In effect, the assumption being
    made is that the position of the whole 'object' (ie. the bracket) can be updated by locating
    bracket_grasp. In the usage above the arm moves to the planning position for
    bracket-grasp and then centers itself about the object between its fingers. Notice that the
    final position of the arm may very well not be bracket-grasp (because of the
    accommodation during the centering). Therefore, the bracket might not be where it was
    planned to be. This discrepancy between the planned world and the 'actual' world has to
    be reconciled. The simplest assumption (and the assumption being used here) is that the
    only difference between the planned location and the actual is that the 'whole' bracket has
    been moved along the line between the fingers so that bracket-grasp is where the arm
    found it. More complicated updating could be done by visually locating the bracket and
    reseting bracket or by feeling the bracket two or three times, combining the resulting
    locations into a new estimate of bracket's location, and reseting bracket. Notice that if
    the CENTER moved the arm away from the planned location and no updating were
    done, the AFFIX statement which follows would affix the bracket to the YELLOW arm in
    such a way that the bracket. was assumed to be at its planning position (which would be
    wrong). The subsequent move to the beam_hole would also be off by the same amount.)
```

```
AFFIX bracket TO YELLOW;
MOVE bracket-hole TO beam-hole;
```

(Notice that the bracket approaches the beam from the side (not from above) because of the DEPR OACH set up for beam-hole. In this example the bracket is assumed to go right next to the beam. This MOVE is a move for the YELLOW arm (because. the bracket is ***AFFIXed*** *to it).* ***From*** *the definition of affixment* ***this*** *means that anything affixed to the YELLOW arm is automatically moved. Thus,* ***bracket,*** *brachet,hole, and bracket-grasp are all updated. The fact that the move was specified by mentioning bracket-hole (and not YELLOW) does not change the automatic updating within the graph structure. Notice, in particular, that this is quite different from:*

AFFIX bracket TO YELLOW
bracket-hole ← beam-hole

which would change the value of bracket-hole and the relative position between bracket and bracket-hole, but leave YELLO W and bracket unchanged.]

```
OPERATE BFINCERS WITH OPENING=3*CM;
MOVE BLUE TO bolt;
```

(The station's APPROACH is used since the bolt is not affixed to anything.)

```
CENTER BLUE;
bolt ← BLUE;
```

(This insures that the latest value of bolt is used in the AFFIX command below.)

```
AFFIX bolt TO BLUE;
MOVE bolt TO beam-hole + VECTOR(0, 0, -5.3) WRT beam-hole;
```

(This should position the bolt .3 centimeters from the bracket. That is, the YELLOW arm is now holding the bracket right next to the beam (with the bracket-hole aligned with the beam-hole) and the ***BLUE*** *arm is holding the bolt 5.3 centimeters away from the bracket-hole (which is equivalent to beam-hole). But remember that the bracket is I cm thick and the bolt is 4 cm long; thus the tip of the bolt* ***is*** *1.3 cm from the beam-hole* ***(or*** *.3 off of the bracket).}*

```
MOVE BLUE TO ● + VECTOR(0, 0, 5) WRT beam-hole;
   WITH FORCE = 0 ALONG X,Y OF BLUE
   ON FORCE(Z WRT BLUE) > 60*OZ DO STOP BLUE;
```

(The arm stops when the bolt hits the bottom of the hole. No DEPARTURE ***or*** *APPROACH is used because the destination involves the* ***"●"*** *construct.)*

```
OPERATE YFINCERS WITH OPENING = 3*CM;
UNFIX bracket FROM YELLOW;
AFFIX bracket TO beam;
MOVE YELLOW TO YPARK;

OPERATE BFINGERS WITH OPENING = 3*CM;
UNFIX bolt FROM BLUE;
AFFIX bolt TO beam;
MOVE BLUE TO BPARK;

WRITE("Finished");
```

```
END;
```

11.1.2 EXAMPLE TWO

This version adds a number of checks (and some automatic recoveries) for possible run-time errors such as not inserting the bolt. It also utilizes the COBEGIN - COEND capability to describe simultaneous (unordered, independent) actions. Thus, the Yellow arm can be picking up the bracket and positioning it near the beam while the Blue arm is picking up the bolt. Collision avoidance is currently the responsibility of the user.

```
DEFINE OZ="((72.007789*GM*CM)/(SEC*SEC))";

positioning: COBEGIN
   ypickup: BEGIN {pick up bracket by YELLOW)
   OPERATE YFINCERS WITH OPENING=3*CM;
   MOVE YELLOW TO bracket-grasp;
   CENTER YELLOW
      ON OPENING = 0*CM D O
         missed: B EC IN {missed bracket)
         STOP YELLOW;
         SCALAR flag;
         OPERATE YFINGERS WITH OPENING=3*CM;
         MOVE YELLOW
            TO bracket-grasp *DEPROACH(bracket_grasp) DIRECTLY;
               (This should safely move the arm away so the operator can easily insert the
               missing bracket. It moves the arm back out to the bracket_grasp's approach
               point at runtime.)
         WRITE("The bracket is missing. Position it and type '1' to try again");
         READ(flag);
         IF flag ≠ 1 THEN ABORT ("Giving up; you didn't type '1'");
               {The ABORT stops everything, saves the world, and forces the operator to
               deal with the problem at supervisor level, possibly investigating the saved
               information, reinitializing the world to some previous state and restarting.)
         MOVE YELLOW TO bracket-grasp DIRECTLY;
               (this results in a simple move without a DEPARTURE or an APPROACH.)
         CENTER YELLOW
            ON OPENING=0*CM DO ABORT("I tried twice; I give up!");
         END missed;

   YELLOW ←← bracket-grasp;
         (This tells the compiler that the yellow arm can be assumed to be at bracket-grasp
         no matter how control got Acre, eg. possibly moving away and retrying the grasp.
         The "←←" specifies that the planning value of bracket_grasp should be used to
         update the compiler's view of where the YELLO W is.)
   bracket-grasp ← YELLOW;
```

```
        {This generates code to be run at run-time which updates the frame bracket-grasp
        (which in turn updates bracket and bracket_hole). The result is that the following
        AFFIX uses the best run-time value of the brachet's position.)
    AFFIX bracket TO YELLOW;
    MOVE bracket-hole TO beam-hole + VECTOR(0, 0, 1.3) WRT beam-hole;
        (This uses the STA TION's DEPAR TVRE (since the bracket is not affixed to
        anything) and the beam-hole's approach (since it is the only frame mentioned in the
        destination). T&s move should position the bracket just off of the beam. The next
        motion pushes it up against the beam.)
    MOVE YELLOW TO ⊗ + VECTOR(0, 0, .5) WRT beam-hole
      ON FORCE(Z WRT beam-hole) > 50%OZ DO STOP YELLOW
      ON ARRIVAL DO ABORT ("I seem to have gone too far");
        (Give up if the expected force is not felt. "AR R IVAL" means that the arm reached
        its destination without being stopped by any of the condition monitors. In this case
        this means that the arm did not reach the expected force, which means that
        something went wrong. The STOP YELLOW disables all condition monitors for the
        yellow arm.}
    END ypickup;

    bpickup: BEGIN (pick up bolt by BLUE]
        {Meanwhile the BLUE arm can be picking up the bolt.)
    OPERATE BFINGERS WITH OPENING=3%CM;
    MOVE BLUE TO bolt;
    CENTER BLUE;
        {Assume everything is OK,)
    bolt ← BLUE;
    AFFIX bolt TO STATION;
    END bpickup
COEND positioning;

{The bracket should be positioned next to the beam and the BLUE arm should be holding the
bolt.)

MOVE bolt TO beam-hole + VECTOR(0, 0, -5.3) WRT beam-hole
    WITH DEPROACH(beam_hole);
      (This should position the bolt .3 centimeter off of the bracket,)

(Now begin a search just in case the bolt doesn't immediately go in the hole: make .2 cm
steps around in a spiral; if the bolt does not go in within nine tries, abort the program.)
FRAME set; SCALAR n;
      {n is the number of attempts.)
n ← 0;
set ← BLUE;
      (Save initial arm position.]
SEARCH BLUE
    INCREMENT .2%CM
    ACROSS PLANE(NILVEC,Z WRT beam-hole)
    REPEATING
      inserting: BEGIN
```

```
      MOVE BLUE TO ⊛ + VECTOR(0, 0, 1.6) WRT beam-hole
        ON FORCE(Z WRT beam-hole) > 60*OZ DO
           missed: BEGIN
           STOP BLUE;
           n ← n + 1;
           IF n > 9 THEN ABORT ("Giving up the search");
           MOVE BLUE TO set
           END missed
        ON ARRIVAL DO TERMINATE;
              {This means that if the MOVE succeeds in reaching its goal, stop the search.
              TERMINATE is a key word within SEARCHs.}
      END inserting;

BLUE cc beam-hole + VECTOR(0, 0, 3.7) WRT-beam-hole;
    {Expect to Rave the bolt (which is 4 cm long) .3 cm into the hole.}

MOVE BLUE TO ⊛*FRAME(ROT(Z, 90*DEG), VECTOR(0, 0, 4))
   WITH FORCE = 0 ALONG X,Y OF BLUE
   ON FORCE(Z WRT BLUE) > 60*OZ DO STOP BLUE;
        {This moves the arm 4 cm straight ahead and twists it 90 degrees about its Z axis
        (ie. straight ahead). Thus it moves ahead and twists.)

disengage: COBEGIN
   foryellow: BEGIN
   OPERATE YFINGERS WITH OPENING = 3*CM;
   UNFIX bracket FROM YELLOW;
   AFFIX bracket TO beam;
   MOVE YELLOW TO YPARK
   END foryellow;

   forblue: BEGIN
   OPERATE BFINGERS WITH OPENING = 3*CM;
   UNFIX bolt FROM BLUE;
   AFFIX bolt TO beam;
   MOVE BLUE TO BPARK .
   END forblue
COEND disengage;
WRITE("Finished");
END;
```

II.1.3 EXAMPLE THREE

This example employs a text macro to simplify definitions, a macro to shorten the code for searching, and a library routine to grasp things. The library routine is supposed to cover a number of possibilities and provide for a number of parameters. Since library routines can be

called with a subset of their parameters filled in, the routine's flexibility is not oppressive for those users who just want to do something simple.

```
DEFINE define_wrt(new_frame, mainframe, position) =
      "new-frame ← mainframe * position;
       AFFIX new-frame TO mainframe";
```

A typical call might be:

```
define_wrt(bracket_hole, bracket, FRAME(ROT(X,180*DEG), VECTOR(5.1, 2, 0));
```

which would expand into:

```
bracket-hole ← bracket * FRAME(ROT(X, 180*DEG), VECTOR(5.1, 2, 0));
AFFIX bracket-hole TO bracket;
```

The following macro produces a string of tokens which imply a compile-time check on the value of the conditional expanded by the parameter RIGID. If RIGID evaluates to TRUE then the token sequence which rigidly affixes the new frame to the main frame is used.

```
DEFINE DEFINE_WRT(new_frame, mainframe, position, rigid) =
  "newframe ← mainframe * position;
   PLAN IF rigid
      THEN AFFIX new-frame TO mainframe RIGIDLY
      ELSE AFFIX new_frame TO mainframe";
```

Another, more complicated macro to facilitate a normal search:

```
DEFINE normal_search(the_arm, increm, dist_fwd, stopping-force, num_tries) =
      "BEGIN (This BEGIN is part of the macro code.)
       FRAME set; SCALAR n;
            {n is the number of attempts.}
      n ← 0;
      set ← the-arm;
            (Save initial arm position.)
      SEARCH the-arm
         INCREMENT increm
       ACROSS PLANE(NILVEC, Z WRT the-arm)
         REPEATING
            insertion: BEGIN
            MOVE the-arm TO * + (dist_fwd*Z) WRT the-arm
               ON FORCE(Z WRT the-arm) > stopping-force DO
                  missed: BEGIN
                  STOP the-arm;
                  n ← n + 1;
```

```
                IF n > num_tries THEN ABORT(""Giving up"");
                MOVE the-arm TO set;
                END missed
            ON ARRIVAL DO TERMINATE
        END insertion;
    ASSERT the-arm = *(set) + VECTOR(0, 0, distfwd);
        (This changes the compiler's view to believe that the arm succeeds on the first
        attempt, and hence the planning value for the arm will be the distance forward
        plus set.)
END";
```

Notice that a pair of adjacent quotes inside of a macro definition (delimited by quotes) denotes a single quote.

A typical call would be:

```
normal_search(YELLO W, .2*CM, 1.6*CM, 60*OZ, 9);
```

The above macro could easily be made into a library routine as follows:

```
ROUTINE normal_search(FRAME the-arm; DISTANCE SCALAR increm, distfwd;
                FORCE SC AL AR stopping-force;
                SCALAR num_tries(DEFAULT 9));
  BEGIN
  :
  END;
```

The corresponding call:

```
normal_search(YELLOW, .2*CM, 1.6*CM, 60*OZ, 9);
```

The "9" is a default value if no value is specified in the call. Thus, by naming the parameters the same call can be made by:

```
normal_search(the_arm=YELLOW, distfwd- 1.6*CM,
   stopping_force=60*OZ, increm=.2*CM);
```

Notice that the order is not important if the parameters are named.

The following routine is a library routine to grasp things. Basically it does the following:

(1) Optionally open to an opening_before_departure.

(2) Depart via a departure (if there is one; a special-departure can be specified).

(3) Start opening the fingers to the opening-for-approach at the departure point (if special-departure is specified, use it. Otherwise, use the standard DEPROACH value.).

(4) Approach the grasping-point via the APPROACH (if a special-approach is specified, use it).

(5) Center on the object. (If the fingers close so that the opening is less than (thickness - .10) call the operator and give him one chance to re-position the object and try again.)

(6) Upon successfully centering on the grasp-point, update the object's position by assigning the grasp-point the current hand location (this, of course, assumes that either the grasp-point and the object are the same frame or that the grasp-point is RIGIDLY affixed to the object).

Notice that this routine can be used by either arm.

```
ROUTINE grasp(TR ANS special-departure, special-approach;
        FRAME ATOM the-arm (DEFAULT YELLOW);
        FRAME object, grasp-point, thing_ob ject_affixed_to;
        DISTANCE SCALAR opening-before-departure,
           opening-for-approach(DEFAULT 15*CM),
           thickness(DEFAULT .3*CM));
        {Special_depart ure is a trans for the relative position of departure.
        Special-approach is a trans for the relative position of the approach.
        Thing-object,ajjixed,to is the name of the frame that the object is affixed to (if
        there is one) bejore the grasp routine is called. It is used to specify from what the
        object should be unfixed upon being grasped. Thickness is defaulted to .3*CM so
        that the condition monitor ON OPENING < (thickness -.2*CM) DO . . . will do a
        reasonable thing.)

  grasping: BEGIN
  ATOM the-fingers;
  CLAUSE t, u;
  PLAN IF *(the_arm) = BLUE
     THEN the-fingers ←← BFINGERS
     ELSE the-fingers ←← YFINGERS;
        (This sets up the 'atom the_fingers to expand into the correct device name for the
        OPERA TE statements (depending upon the choice of arm).)
  PLAN IF SPECIFIED(opening-before-departure) THEN
     OPERATE *(the_fingers) WITH OPENING-opening-before-departure;

        (The next statement sets up a clause, u, which contains the phrase
        "WITH APPROACH = <the special>" or NILDEPROACH depending upon whether
        or not a special approach has been specified. This constructed phrase is used in
        two or three places below to insure that the desired approach is being used.)
  PLAN IF SPECIFIED(special_approach)
```

```
    THEN u ←← CLAUSE(WITH APPROACH = special-approach )
    ELSE u ←← NILCLAUSE;
  PLAN IF SPECIFIED(special_departure)
    THEN MOVE *(the_arm) TO grasp-point
         WITH DEPARTURE=NILDEPROACH
         VIA *(the_arm)* special-departure THEN
           BEGIN
           OPERATE *(the_fingers)
             WITH OPENING-opening-for-approach
           END
         *(u)
    ELSE MOVE *(the_arm) TO grasp-point
         WITH DEPARTURE=NILDEPROACH
         VIA *(the_arm)* DEPROACH(grasp_point) THEN
           BEGIN
           OPERATE *(the_fingers)
             WITH OPENING=opening_for_approach
           END
         *(u);

  CENTER *(the_arm)
    ON OPENING < (THICKNESS-.2&M) DO
      missed: BEGIN
      STOP *(the_arm);
      SCALAR flag;
      OPERATE the-fingers WITH OPENING=opening_for_approach;
      PLAN IF SPECIFIED(special_approach)
        THEN BEGIN (move to special approach point)
             MOVE *(the_arm) TO *(the_arm)* special-approach
                  DIRECTLY
           END
        ELSE BEGIN (use the normal approach)
             MOVE *(the_arm)
               TO *(the_arm)* DEPROACH(grasp_point)
               DIRECTLY;
           END
      WRITE("Grasp failed; Type a '1' to retry");
      READ(flag);
          {This is simply "wait for proceed".)
      IF flag ƒ 1 THEN ABORT;
      MOVE *(the_arm) TO grasp-point DIRECTLY;
      CENTER *(the_arm)
        ON OPENING < (THICKNESS-.2&M) DO ABORT ("Closed on air");
      END missed;

  grasp_point ← *(the_arm);
  PLAN IF SPECIFIED(thing_object_affixed_to) THEN
    UNFIX object FROM thing-object-affixed-to;
  AFFIX object TO *(the_arm);
```

```
END grasping;
```

The following is a typical call on such a routine:

```
grasp(the_arm=YELLOW, object=bracket,
      grasp_point=bracket_grasp,
      special_approach=FRAME(ROT(Z,90*DEG),VECTOR(0,0,-3)),
      opening_for_approach=3*CM);
```

which expands into:

```
MOVE YELLOW TO bracket-grasp
. WITH DEPARTURE=NILDEPROACH
   VIA YELLOW*FRAME(NILROT,10*Z) THEN
      BEGIN
      OPERATE YFINCERS WITH OPENING=3*CM
      END
   WITH APPROACH =FRAME(ROT(Z,90*DEG), VECTOR(O,O,-3));
CENTER YELLOW
   ON OPENING <.2*CM DO
      missed: BEGIN
      STOP YELLOW;
      SCALAR flag;
      OPERATE YFINGERS WITH OPENING=3*CM;
      MOVE YELLOW
         TO YELLOW*FRAME(ROT(Z,90*DEG), VECTOR(0, 0, -3))
         DIRECTLY;
      WRITE("Grasp failed; Type a '1' to retry");
      READ(flag);
      IF flag ≠1 THEN ABORT;
      MOVE YELLOW TO bracket-grasp DIRECTLY;
      CENTER YELLOW
         ON OPENING <.2*CM DO ABORT ("Closed on air");
      END missed;
bracket-grasp ← YELLOW;
AFFIX bracket TO YELLOW;
```

Finally, the whole task is made into a library routine so it can be 'called' (ie. expanded) as a **subtask** from a higher level task.

```
DEFINE OZ="((72.007789*GM*CM)/(SEC*SEC))";

ROUTINE bolt-on-bracket;
   whole-task: BEGIN
   PLAN IF *(YELLOW)≠ YPARK
      THEN PLAN ERROR("The yellow arm is not planned to be in its
         park position, contrary to assumption in routine bolt-on-bracket");
```

```
PLAN IF FORM(AFFIXED, ANYTHING, YELLOW)
   THEN PLAN ERROR("Something is affixed to the yellow hand;
      the routine bolt-on-bracket expects the hand to be empty.");
```

(This type of compile-time check and warning to the user is very useful for insuring that tire interface assumptions for routines are met in the planning world just before the routine is expanded. Notice that there is a built-in procedure, PLAN ERROR, which prints the included message at compile-time and stops the compilation. There is also a compile-time WRITE statement, PLAN WRITE ("..."). These two different 'output' statements ate used so that the user can generate WRITE statements during the compilation of a program.)

```
COBECIN
   ypickup: BEGIN (Pick up bracket with YELLOW}
   grasp(grasp_point=bracket_grasp, object=bracket,
      opening_for_approach=3*CM);
   MOVE bracket-hole TO beam-hole + VECTOR(0, 0, 1.3) WRT beam-hole;
   MOVE YELLOW TO ⊗ + VECTOR(0, 0, .5) WRT beam-hole
      ON FORCE(Z WRT beam-hole) > 50*OZ DO STOP YELLOW
      ON ARRIVAL DO ABORT("I Seem to have gone too far.");
   END ypickup;

   bpickup: BEGIN (Pick up bolt with BLUE]
   grasp(the_arm=BLUE, object=bolt, grasp-point-bolt,
      opening-for-approach= 3*CM)
   END bpickup
COEND;

MOVE bolt TO beam-hole + VECTOR(0, 0, -5.3) WRT beam-hole;
normal_search(BLUE, .2*CM, 1.6*CM, 60*OZ, 9);
      (Assume that the bolt is now in the hole.)
MOVE BLUE TO ⊗ * FRAME(ROT(Z,90*DEG), VECTOR(0, 0, 4))
   ON FORCE(Z WRT BLUE) > 60*OZ DO STOP BLUE;

disengage: COBECIN
   foryellow: BEGIN
   OPERATE YFINGERS WITH OPENING = 3*CM;
   UNFIX bracket FROM YELLOW;
   AFFIX bracket TO beam;
   MOVE YELLOW TO YPARK
   END foryellow;

 forblue: B E G I N
   OPERATE BFINCERS WITH OPENING = 3*CM;
   UNFIX bolt FROM BLUE;
   AFFIX bolt TO beam;
   MOVE BLUE TO BPARK
   E N D forblue
COEND disengage
END whole-task;
```

11.2 EXAMPLES OF COORDINATED ACTION

These two examples take into account some of the more subtle aspects of assembly such as freeing the bracket while trying to insert the bolt in the hole and changing the speed of the driver dynamically.

The following section of code is designed to simultaneously free the YELLOW arm and move the BLUE arm to insert the bolt. The freeing of the YELLOW arm is to allow the bracket to accommodate slightly along the surface of the beam as the BLUE arm tries to insert the bolt.

```
MOVE bolt TO beam-hole + VECTOR(0, 0, -5.3) WRT beam-hole;
    (Remember that the bolt is in the BLUE hand.)
MOVE YELLOW TO ⊗
  WITH FORCE = 0 ALONG X,Y OF beam-hole
  ON DURATION > 0*SEC DO
    insertion: BEGIN
        (Notice that "DURATION > 0*SEC" is an approximation to simultaneous motion.)
    normal_search(BLUE, .2*CM, 1.6*CM, 60*OZ, 9);
        (Assume that the bolt is now in the hole.)
    MOVE BLUE TO ⊗ * FRAME(ROT(Z,90*DEG), VECTOR(0, 0, 4))
      ON FORCE(Z WRT BLUE) > 60*OZ DO STOP YELLOW;
    END insertion
  ON DURATION > 4*SEC DO ABORT("Operation took too long");
      (The "ON DURATION > 4*SEC DO ABORT" will generate an error if the
      insertion takes more than 4 seconds. The error will force the operator to deal with
      the situation at supervisor Level.1
```

Without the SEARCH this could be accomplished in "weak" synchrony:

```
MOVE bolt TO beam-hole + VECTOR(0, 0, -5.3) WRT beam-hole;
MOVE [BLUE: YELLOW)
  TO [⊗ + VECTOR(0, 0, 1.6) WRT BLUE : ⊗]
  WITH [: FORCE = 0 ALONG X,Y OF beam-hole]
  ON [FORCE(Z WRT BLUE) > 60*OZ : ] DO [STOP : STOP];
```

It is awkward to include the SEARCH in such a scheme. In fact, this type of coordination comes up in a number of other places. For example, if you want to operate a device (eg. the DRIVER) and move an arm or camera "at the same time." Events and synchronizing primitives have been added to solve these control problems. Consider the following way of programming this task:

```
EVENT y-ready, b-ready;
    {y_ready is an event signalling that the YELLOW arm is ready to move, b-ready
    indicates that the BLUE arm is ready to move.)
MOVE bolt TO beam-hole + VECTOR(0, 0, -5.3) WRT beam-hole;
bolt-insert: COBEGIN
  free-yellow: BEGIN
  SIGNAL y-ready;
```

```
    WAIT b_ready;
    MOVE YELLOW TO ⊗
      WITH FORCE = 0 ALONG X,Y OF beam-hole
      ON DURATION > 4*SEC DO ABORT("Took too long");
    END free-yellow

    blue-insert: BEGIN {Use blue to insert bolt)
    SIGNAL b-ready;
    WAIT y_ready;
    normal_search( BLUE, .2*CM, 1.6*CM, 60*OZ, 9);
        (A ssume that the bolt is now in the hole.)
    MOVE BLUE TO ⊗ * FRAME(ROT(Z,90*DEG), VECTOR(0, 0, 4))
      ON FORCE(Z WRT BLUE) > 60*OZ DO STOP YELLOW;
    END blueinsert;
  COEND bolt-insert;
```

Consider the problem of inserting in a screw and checking to make sure that it does not bind. If, after a short time, the screw does not bind, the speed of the DRIVER can be increased. However, if it DOES bind, everything should stop and the DRIVER should be reversed to try to unbind the screw.

```
  EVENT d_ready, b_ready;
SCALAR sp, flag;
  sp ← 30;
  flag ← 1;
  WHILE flag DO
    screw-loop: BEGIN
    move-screw: COBEGIN (Move and screw simultaneously]
      drive: BEGIN
      SIGNAL d_ready;
      WAIT b_ready;
      OPERATE DRIVER
        WITH VELOCITY = sp
        ON DURATION > 8*SEC DO ABORT("Took too long");
      END drive

      downward-force: BEGIN
      SIGNAL b_ready;
      WAIT d_ready;
      MOVE BLUE TO ⊗
        WITH FORCE = 0 ALONG Z OF BLUE
        WITH FORCE = 40*OZ ALONG Z OF BLUE
        bind: ON TORQUE(Z WRT BLUE) > 80*OZ DO
          bound: BEGIN
          DISABLE catch-ok;
          STOP BLUE;
          STOP DRIVER;
          COBECIN {Try to unbind by reversing the driver)
```

```
            unscrew: BEGIN
            SIGNAL d-ready;
            WAIT b_ready;
            sp ← -60;
            OPERATE DRIVER
               WITH VELOCITY = SP
               ON DURATION > 4*SEC DO ABORT("Can't unbind");
            END unscrew

            upward-force BEGIN
            SIGNAL b-ready;
            WAIT d_ready;
            MOVE BLUE TO ⊗
               WITH FORCE = 0 ALONG Y, X-OF BLUE
               WITH FORCE = 40*OZ ALONG Z OF BLUE
               out-ok: ON FORCE(Z WRT BLUE)<20*OZ DO
                  BEGIN
                  STOP DRIVER;
                  STOP BLUE;
                        {Leave flag true for retry.}
                  END
               too-much-time: ON DURATION>4*SEC DO ABORT;
            END upward-force
         COEND
         END bound
      catch-ok: ON DURATION > 1*SEC DO
         BEGIN
         DISABLE bind;
         ENABLE torqued_in_ok;
         sp ← 60; {maybe this should be CRITICAL.]
         END
      torqued_in_ok: DEFER ON TORQUE(Z WRT BLUE) > 80*OZ DO
         BEGIN
         STOP DRIVER;
         STOP BLUE;
         flag ← 0; (indicating no retry}
         END;
   END downward-force
COEND move-screw
END screw-loop;
```

II.3 A 'VERY HIGH LEVEL' EXAMPLE

This very short example demonstrates the use of assembly-oriented special primitives to simplify a task specification, as well as some of the object description conventions used by those primitives. Here, the task is the same as that of subsection II.1.1. For a fuller explanation of the use of such primitives and another, longer example, see Chapter 4.

```
FRAME beam, bracket, bolt;
FRAME bracket-bore, beam-bore;
FRAME bolt-grasp, bracket-handle;

(We must first describe the various components. We expect that eventually the process of
making such descriptions will become very largely automated, as computer programs begin to
play an increasingly active role in mechanical design. See Section 4.7.)

ASSERT FORM(TYPE, beam, object);
ASSERT FORM(GEOMED, beam, "beam.B3D[AL,HE]"); (Shape description]
ASSERT FORM(SUBPART, beam, beam-bore);
ATTACH beam-bore TO beam RIGIDLY AT TRANS(ROT(Y,90),VECTOR(0,1.5,6));

ASSERT FORM(TYPE, bracket, object);
ASSERT FORM(GEOMED, bracket, "BRACK.B3D[AL,HE]"); (Shape description.)
ASSERT FORM(SUBPART, bracket, bracket-bore);
ASSERT FOR M(SUBPART, bracket, bracket-handle);
ATTACH bracket-bore TO bracket RIGIDLY AT TRANS(ROT(X, 180),VECTOR(5.1,2,0));
ATTACH bracket-handle TO bracket RIGIDLY AT TRANS(ROT(X,180),NILVEC);

ASSERT FORM(TYPE, bolt, SHAFT);
ASSERT FORM(DIAMETER, bolt, 0.5*CM);
ASSERT FORM(TOP_END, bolt, head_type1);
ASSERT FOR M( BOTTOM-END, bolt, tiptypel);
ASSERT FORM(TYPE, tiptypel, FLAT-END);

ASSERT FOR M(TY PE, bracket-bore, BOR E);
ASSERT FORM(DIAMETER, bracket-bore, 0.502*CM);
ASSERT FORM(LENGTH, bracket-bore, 0.5*CM);
ASSERT FORM(TOP_END, bracket-bore, bracket,holel);
ASSERT FORM(BOTTOM_END, bracket-bore, bracket,holel);

    (Et cetera)

{Also, describe how things go together:}
ASSERT FORM(TYPE, beam-assembly, ASSEMBLY);
ASSERT FORM(SUBPART, beam-assembly, beam);
ASSERT FORM(SUBPART, beam-assembly, bolt);
ASSERT FORM(SUBPART, beam-assembly, bracket);

ASSERT FORM(bracket, FITS-ONTO, beam-assembly, AT,
```

```
   TRANS(ROT(Y,90),VECTOR(5.1,2,0));
ASSERT FOR M(bolt, FITS-ONTO, beam-assembly, AT,
   TRANS(ROT(Y,90),VECTOR(5.1,2.3,0));

ASSERT FOR M(MATED, beam,hsurf, bracket-bottom);
ASSERT FORM(ALIGNED, beam-bore, bracket-bore);
ASSERT FORM(RUNS_THRU, bolt, bracket-bore);
ASSERT FORM(RUNS_THRU, bolt, beam-bore);
```

{Et cetera.)

(Now, describe the initial scene. Here, assume that the initial object locations are known precisely.)

```
bracket ← FRAME(NILROT,VECTOR(20,40,0));
beam ← FRAME(NILROT,VECTOR(10,60,0));
bolt ← FRAME(ROT(Y,180),VECTOR(30,50,5));

grasp bracket AT TRANS(ROT(Y,180),2*Z) WITH YELLOW;
```

(The system will use its internal model of the bracket to fill in the expected hand opening.)

```
FIT bracket ONTO beam-assembly
      USING YELLOW
      AFTERWARDS HOLD bracket WITH YELLOW;
```

(The system will use the object description information to fill in the exact location to which to move the bracket. Also, it will pick appropriate techniques to ensure that the bracket is appropriately aligned. The AFTER WARDS clause tells the system that it is to use the yellow arm to hold the bracket in place]

```
INSERT bolt INTO bracket-hotel USING BLUE;
```

(Once again, the system will fill in the details, such as how the bolt is to be grasped, how it should be brought to the hole, how it will be pushed in, and so forth.}

```
RELEASE bracket; (Since the bolt now holds it on.)
```

APPENDIX III
RUNTIMESYSTEM

This appendix discusses in greater detail some of the aspects of the **runtime** system, which resides on the PDP 11 as a set of programs executing compiled code, operating devices in real time and receiving sensory input.

III.1 THE **RUNTIME** SCHEDULER

As mentioned earlier, in Chapter 5, the **runtime** scheduling is managed through a combination of priority level assignments to various types of processes and a time-slot request list. The PDP-I I hardware provides eight processor priority levels. These are assigned in the AL system as follows:

7. AD (Analog-to-digital converter), joint servoing
6. Clock, calendar
5. <spare>
4. condition monitors; Interrupt handlers for
various condition-checking devices (eg finger pads).
3. servo predictor
2. <spare>
1. Interpreters, scheduler for background stuff.
0. Interpreters

The AL system keeps a calendar of things that must be done in each time interval. With time slot is associated:

a. An AD command list which is to be started.
b. A queue of procedure calls to make at various priority levels.

Typically, a servoing operation will have two "phases", one which runs at level 7 as a response to an AD-done interrupt and which is responsible for emitting the new drive, and a somewhat lower priority one which requests a new time slot from the calendar management routine and sets up the correction phase for the new slot- As previously indicated, this first phase is "scheduled" by putting a pointer to the appropriate AD command list into the "AD request" part of a calendar time slot. The second phase is scheduled merely by entering it onto the calendar queue of things to be requested in the same tick. Joint servos are described more fully in the next section.

If a non-critical process (eg, a condition monitor) needs a "consistent" set of AD measurements, it can get them by setting up the appropriate AD command list, finding a time slot for taking the measurements, and then placing a request that the computation that is to use the set of measurements be started up at the time slot after the one in which the measurements are made.

In cases where a command list is too long to be finished in one time slot, the process requesting the measurements must reserve two (or more) contiguous slots. This is done by placing the command list id in the first slot and a special flag value (perhaps -1) into the remaining slots, so that no other processes will try to reserve them.

III.2 TRAJECTORIES

A trajectory for the hand is generated at compile time under the assumption that the planning values for the initial point, departure point, via points, arrival point and final position are accurate.

If at run time it is found that some or all of these planned positions have moved slightly it becomes necessary to modify the planned trajectory to pass through the actual positions. If the actual positions are only slightly different from the planned positions then the trajectory is still almost optimal, that is, it still has most of the properties with which it was designed. If the deviation from the planned values to the actual are great then the trajectory is no longer optimal. To plan a new trajectory would again optimize the move, but only if the time to compute is less than the time saved is it worth recomputing. At present this is not the case, so no recalculation of trajectories is done. Instead, the following trajectory modification step is performed:

Before the move is executed, it is prepared by computing the discrepancies between actual locations and planned locations. Fifth degree interpolating polynomials (with zero initial and final velocity and acceleration) are computed to be added into the planned polynomials to bring the planned trajectory into line with reality. The joint angles associated with a frame are stored along with its matrix, so this often does not involve much calculation, unless the frame has been changed since these calculations were done last. Also at this time the joint inertias and gravity loadings are calculated and stored in the value cell of relevant frames.

III.3 JOINT SERVOINC

Any coordinated motion of the arm can be expressed as six time dependent motions, one for each joint; the coordinated motion is parameterized in terms of time. The problem of servoing the arm, or arms, is thus reduced to a problem of servoing a number of joints with respect to time.

A joint servo has two parts: a drive part and a predictor part. As mentioned before, the drive part is run at priority level 7. When it finishes, the servo enters priority level 3 for the predictor. First, the predictor reserves a time for the next run of this servo. The delay is chosen based on considerations of joint response time, joint velocity, and availability of time slots.

Now the predictor evaluates the motion polynomial for the time which it has reserved. This evaluation may take into account an interpolating polynomial used for last-minute trajectory modification, as well as any offset that might be necessary due to modifications being made during the motion itself. These calculations give the predicted set point. The predicted velocity and acceleration are obtained by difference techniques based on recent set point values, The joint inertia and gravity force loading are interpolated. The gravity loading is added to the product of the predicted acceleration and the joint inertia to yield a predicted drive.

If this joint has multiple wipers then the appropriate wiper to read the joint position is determined. Then the joint calibration is applied to the set point to yield the expected

potentiometer reading for the joint at the reserved time. The servo gains, which are dependent on joint inertia, are next calculated, and finally the servo equation is set up in terms of observed position and velocity. The form of the servo equation is dependent on whether the joint is being run with position, velocity, or force servoing. Having done all this predictive work, the joint servo dismisses control.

When the reserved time occurs, the drive part of the servo runs in priority level 7. The drive part measures the position and velocity, evaluates the servo equation prepared by the predictor, applies friction compensation and drives the joint. This is a very fast computation and minimizes any delay between observation and action. The predictor is then run again for the next servo scheduling, as described above.

Upon completion of the motion, or if some error should occur, or if some other process requests that the joint stop, completion codes are set for the joint, and then the servo terminates.

The advantage of this servo scheme is that it allow flexible scheduling: each joint can run at its own required repetition rate. As the joint knows when it will be run next it is possible to pre-compute most of the drive and thus reduce the servo delay.

Each servo routine has a control block which includes a status register. In the case of a joint servo the status register contains the following bits:

RUN	joint is running or about to be run
FIRST	first time through loop for this motion.
FINAL	in final state, nulling errors
STOP	stop this joint, or joint is stopped
EXFORCE	joint stopped due to excessive force.
ADERR	a/d error
NONEX	joint is down or does not exist
STERR	servo was not run on schedule
SERVO	position servo
VELS	velocity servo
FORCE	exert force
WOB	perturb this joint while running
NUL	null errors at end and stop

When the servo is started up for the first time, it is given certain information, including which joint it should servo, what the properties of that joint are, what polynomial to follow, the predicted gravity torque and inertia loadings.

This system allows us to move the arm and to carry loads; it is possible to exert forces along various free directions. The system as it is described here is incapable of interacting with live loads, springs, partially submerged objects and other objects with complex reactions to forces.

III.4 INTERPRETABLE CODE

The runtime interpreters act by interpreting a special kind of code generated by the compiler. The *pseudo operations* available include stack manipulation, flow-of-control primitives, device control, and arithmetic. Arithmetic routines always take their arguments from the stack, which contains pointers to value cells. Variables are accessed through *environments:* an environment points to all the variables local to a particular block level and also to the environment in force at the next global level. When one interpreter sprouts several subsidiary interpreters (to implement a simultaneous block, for example), each new interpreter gets a new environment which points to the old one; thus they all share global information.

Arguments are stored immediately after those pseudo-instructions which need them.

Here is a list of the pseudo-operations currently available:

STACK OPERATORS

gtval <arg>	The argument has two fields: lexical level and offset. Together, these determine a variable. The value of that variable is extracted from the graph structure and a pointer to it is placed on the stack.
chnge <arg>	The argument again determines a variable. The value currently pointed to by the top of the stack is stored into that variable, and all necessary updating of the graph structure is performed.
pop	pops the stack.
copy <num>	finds the <num>'th element down in the stack (this will be a pointer to some value cell) and copy it to the top.
copys	make a new scalar value cell; initialize it to the same value as the cell currently pointed to by the top of the stack, and push it.
copyv	make a new vector value cell; initialize it to the same value as the cell currently pointed to by the top of the stack, and push it.
copyr	make a new rot value cell; initialize it to the same value as the cell currently pointed to by the top of the stack, and push it.
copyf	make a new frame value cell; initialize it to the same value as the cell currently pointed to by the top of the stack, and push it.
copyp	make a new plane value cell; initialize it to the same value as the cell currently pointed to by the top of the stack, and push it.
copyt	make a new trans value cell; initialize it to the same value as the cell currently pointed to by the top of the stack, and push it.
flush	clears the stack.

ARITHMETIC

Arithmetic routines are supplied for all the operations described in subsection 2.1.9. The stack contains pointers to the value cells needed as arguments. After the operation is completed, all argument pointers are popped from the stack, and a pointer to the result value cell is pushed onto the stack.

FLOW OF CONTROL

proc	Procedure call; takes as arguments the destination address, the argument list. All value parameters should first have been copied into temps.
return	Procedure return
sprout	Start up a new interpreter. The single argument tells where its code is to be found.
enable <arg>	start up an on-monitor with location of status word <arg>.
disable <arg>	the on-monitor with location of status word <arg> is disabled.
wait	wait until all descendant (non on-monitor) processes are dead. Then kill descendant move on-monitors and continue.
terminate	terminate this process. Should first call "wait".
jump <arg>	unconditional jump to indicated location in interpreter code.
jumpp <arg>	conditional jump on positive element at top of stack.
jumpz <arg>	conditional jump on zero element at top of stack.
nop	no-op.

ARM AND DEVICE CONTROL

prepmove <arg>	<arg> points to the move vector. Trajectory modification happens now.
startmove	sprouts joint servos and move-monitors
search <arg>	<arg> points to the search vector.
stop <arg>	<arg> encoding of what devices must be stopped.

INPUT AND OUTPUT

Some sort of I/O will be implemented, most likely including string output to the supervisor, error message output, and input (from supervisor or from coresident routines) of value cells.

DEBUGGING AIDS

source <arg>	notes that <arg> is where the interpreter is now in source code.
tellsou rce	output current source location to the 10.
step	begins step mode, which does one interpretation at a time, requires message to continue.
offstep	turns off step mode; normal speed is resumed.

III.5 ALGORITHMS FOR USE OF GRAPH STRUCTURE

These are the algorithms (written in an Algol-like fashion) used to find values for variables in the graph structure and to change those values.

```
PROCEDURE invalidate (POINTER(NODE) n);
    IF invmark(n)-0 THEN
        BEGIN COMMENT: This cell currently marked valid;
        POINTER p;
        invmark(n)c - 1;
        p ← dependents(n);
        WHILE p≠NULL DO
            BEGIN COMMENT: Mark all dependents as invalid;
            invalidate(p);
            p ← link(p)
            END
        END;


PROCEDURE change (POINTER(NODE) n; POINTER(VALUE) vnew);
    BEGIN
    COMMENT: This procedure is called in order to explicitly assign
        a new value, vnew, to node n;
    POINTER(VALUE) vold;
    invalidate(n);
    vold ← value(n);
    value(n)←vnew;
    p ← changer(n);
    WHILE p≠NULL DO
        BEGIN COMMENT: Handle all changers;
        APPLY(code(p),vold,vnew);
        p ← link(p);
        END;
    invmark(n) ← 0;
    END;


POINTER(VALUE) PROCEDURE getvalue (POINTER(NODE) n);
    BEGIN
    IF invmark(n)≠0 THEN evalnode(n, time ← time+1);
    RETURN(value(n));
    END;
```

```
PROCEDURE evalnode (POINTER(NODE) n, INTEGER t);
    BEGIN COMMENT: Put a good value in the value cell of n.
        t is used to break cycles;
    IF invmark(n)=0 fl invmark(n)=t THEN RETURN;
    invmark(n) ← t;
    p ← calculator(n);
    WHILE p ≠ NULL DO
        BEG IN "cloop"
        POINTER(node) d;
        d ← needed(p);
        WHILE d ≠ NULL DO
            BEGIN
            evalnode(node(d),t);
            IF invmark(dep(d))≠0 THEN
                BEGIN
                p ← next(p);
                CONTINUE "cloop";
                END;
            d ← next(d);
            END;
        value(n)←APPLY(code(p), args(p));
        invmark(n)←0;
        RETURN;
        END;
    END;
```