FLIGHT TRANSPORTATION LABORATORY
REPORT R 85-7

# POTENTIAL USE OF ARTIFICIAL INTELLIGENCE TECHNIQUES IN AIR TRAFFIC CONTROL

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October 1985

MIT

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FLIGHT TRANSPORTATION
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Cambridge, Mass. 02139

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Presented at the Seminar on Informatics in Air Traffic Control held in Capri, Italy October 16 - 25, 1985 under the sponsorship of the Consiglio Nazionale delle Ricerche and the Commission of the European Communities

October 22, 1985

### Abstract

A.I., or Artificial Intelligence, is a vast field that includes more than the so-called "Expert Systems" that the public seems to identify with A.I. In particular, research in A.I. has created an entirely new mode of operating with computers which raises the level of abstraction at which the computer user (and the programmer) interfaces with the computer, enabling systematic and economical handling of high-complexity problems. These techniques are particularly applicable to Air Traffic Control automation problems which exhibit a high degree of complexity, such as system-wide simulation experiments, flow control procedures, and tactical control supervision. In addition, specific A.I. techniques– such as Expert Systems – have unique specific applications in ATC, for example Airport Runway Configuration planning, passive visual radar, and others.

## 1. INTRODUCTION

The Flight Transportation Laboratory of the Massachusetts Institute of Technology, directed by Professor Robert Simpson, is one of the few academic organization in the United States with a continuous research program in Air Traffic Control problems. The Laboratory has a record of continuous research in this field starting from its creation in the late 1960's, with some 100 reports and technical memoranda on the subject to its credit. Among the past achievements of the Laboratory in this field we can count the early development of CTDI (Cockpit Display of Traffic Information), the Simpson-Sheridan method of determining crew and controller workload, various models for landside and airside airport capacity, collision risk models, radar tracking algorithms, runway scheduling algorithms, and the real-time Air Traffic Control simulation for the Man-Vehicle Systems Research Facility at NASA's Ames Research Center. In addition, we have performed research in the closely related field of Command and Control systems, where very large networks of men and machines combine to communicate information, take decisions, and transmit orders. In this field, we have designed a microcomputer-based, field deployable Command and Control system for the U.S. Air Force's Military Airlift Command, to assist them in the real time scheduling and control of their flights, as well as equivalent systems for civilian airlines.

In the course of our research we have observed with concern that advanced concepts in Air Traffic Control automation – whether developed at the Flight Transportation Laboratory or elsewhere – seldom reach the floor of the Air Traffic Control Centers. A few years ago, for example, an Advanced Enroute Metering and Spacing concept was developed, and actual code was implemented in the NAS system to support it; to our knowledge, this capability is not used in any significant degree in any of the U.S. Air Traffic Control Facilities.

There are critics of the proposed new Advanced Automation System, or AAS, who claim that the algorithms required by that system will never work properly in conjunction with human controllers. While we do not share such negative attitude towards the AAS concept, I must report that we, too, have experienced significant problems in trying to marry a mathematical control algorithm – no matter how advanced and well designed – with a human decision maker. As long as the algorithm's function is "invisible" to the user – such as, for example, a radar tracking algorithm – he does not experience great difficulties working with it. However, when the algorithm interacts directly with the human decision-making process – such as in the detection or resolution of traffic conflicts – we often observe a conflict between the mode of operation of an otherwise excellent algorithm and the mode of operation of the human controller. In extreme cases, test subjects even perceive the automation feature as a hindrance rather than as an aid.

It is precisely because of this problem with the "algorithmic approach" that we have turned to the field of Artificial Intelligence for tools and alternative approaches to the problem of providing the users of Air Traffic Control automation (and here I include the pilot and the flow coordinators as well as the obvious radar controller) with functions that indeed make their job easier, not more difficult. Today, I would like to share some of these experiences, both positive and negative, with you.

It seems only natural to begin this exposition with a brief overview of what Artificial Intelligence is, and what are some of the generic tools it provides; however, I must warn you beforehand that I am *very prejudiced* on the subject of Artificial Intelligence. We at FTL are not experts in Artificial Intelligence; we are fortunate enough to have available to us the considerable resources of M.I.T.'s Artificial Intelligence Laboratory and the Laboratory for Computer Sciences, two of the leading research organizations in this field, but I want to emphasize that we are *users*, and not developers, of Artificial Intelligence technology.

This leads us to a rather biased and result-oriented viewpoint on Artificial Intelligence; for us, A. I. is not a new business, it is just a new way of doing our old business. Therefore, those of you that may have not been exposed beforehand to A. I. should be warned that this will be a rather unorthodox introduction to the field; on the other hand, those of you who may be familiar with A. I. may find this user's viewpoint a refreshing experience, especially if you have been recently subjected to some of the "high pressure" sales pitches that some promoters of Artificial Intelligence seem to be using these days.

## 2. A BIASED INTRODUCTION TO A. I.

Edward Feigenbaum, in his "Handbook of Artificial Intelligence", defines Artificial Intelligence, or "A. I." for short, as "the part of computer science concerned with designing intelligent computer systems". This is a very easy definition to make, since it shifts the burden of definition to another one, namely that of "intelligent computer system". Feigenbaum then proceeds to define intelligent computer systems as those which "exhibit the characteristics we associate with intelligence in human behavior". Unfortunately, this one is not very helpful either, since we now must define intelligence itself, a rather formidable task.

But even if were able to define human intelligence, we would still have a problem, since "intelligent behavior", when applied to computers, cannot be equated with intelligent behavior in general. As little as a hundred years ago, computing the square root of a number was unequivocally a manifestation of human intelligence, since it required a number of decision-making steps depending on the signs of intermediate values, remainders, and so on. Yet to-day, nobody would call the square-root calculating ability of a computer "intelligent behavior".

In view of this inability to satisfactorily define "intelligent behavior" as applied to a computer, some people have slightly altered the classical definition to mean "doing with a computer something you normally don't expect a computer to be able to do". This definition appears to be satisfactory, since taking square roots, for example, is something you expect a computer to do, so a system that takes square roots of numbers is definitely not an Artificial Intelligence system, while a system that composes concert music *does* appear "intelligent", since computers do not usually compose concert music.

The problem with this new definition is that it is self-defeating: the moment one builds a computer system that does something you do not expect a computer to do, it does it, so it ceases to become an "Artificial Intelligence" system. As paradoxical as this may seem, it actually makes some sense: today, one can purchase battery-powered toys at a department store that do a better job at synthesizing speech or playing chess than the most sophisticated experimental equipment did just ten years ago. Are these toys Intelligent Systems? How about the first FORTRAN compiler? Was it an A. I. product? It certainly did something that previously was thought required human intervention, namely write a computer program from complex mathematical expressions.

In view of this difficulty in defining what precisely Artificial Intelligence is, perhaps we should simply describe a little of its history and some of its typical products. A. I. research has traditionally had three distinct objectives: first, to understand the high-level workings of the human brain by constructing functional computer models of human activities, such as vision and reasoning; second, to build computers based on the brain model; and third, to build a "mechanical man", perhaps by combining the results of the other two efforts.

The motivation of the first line of research is a better understanding of the human brain, and any computer functionality that may result from this research is purely secondary. The motivation of the second, to build computer systems – both hardware and software – patterned after the human brain, with the goal of building better computer systems, independently of the specific application.

Now, the third goal is the most elusive one; humans had had the dream of building mechanical replicas of themselves for at least as long as they have dreamed to fly; if we have been able to fulfill the dream of flying, is there any reason we will not be able to build a true robot? Perhaps, but we should be very careful not to identify Artificial Intelligence with *only* this goal. If we do, we will miss what perhaps is the most useful benefits from A. I. research, benefits that, in my opinion, we can begin to enjoy to-day. However, these benefits are not the "intelligent machines" per se, but rather the computer technology that has been developed as a consequence of the quest for machine intelligence, however one may care to define it. I guess I should also add that A. I. is also not only Expert Systems; the current popularity and press coverage that Expert Systems have recently received has caused a lot of people to believe that the only useful product of Artificial Intelligence research consists of Expert Systems.

Historically, Artificial Intelligence had its roots in the discipline of mathematical logic, sometimes also called symbolic logic, the study of the processes by means of which we construct the mental models we call "mathematics". It was with the discovery, by Turing and others, that these symbols could be manipulated and operated upon mechanically with the same ease as numbers – although with a different set of operations, naturally – that the possibility of a computer performing these "intelligent" functions was first postulated. Indeed, Lisp, now considered to be the programming *lingua franca* of the A. I. community, can be considered either a programming language, or a convenient, elegant, and powerful method of expressing mathematical concepts.

The first attempts at using computers to manipulate symbols for a purpose started by defining a simple "problem" to be solved, for example, winning a game of chess. The kinds of problems that early A. I. systems were capable of handling had two common characteristics: the goal, or problem, was very simple to state (such as capturing the opponents' King), but the solution to the problem was complex and non-trivial. The measure of success used in the developments of these game-playing systems was this: could the program play a better game than the people that build it?

The common technique used in these systems was the *generation* of large sets of alternatives, followed by a process of *search* (for a desired solution), usually coupled with procedures that *reduce* the number of alternatives to be evaluated to a reasonable subset. In a chess-playing[1] program, the alternatives are the sequence of legal moves and counter-moves that can be made by the program and its opponent from the current state of the board, alternatives that can be structured as a tree; the search consists in the successive evaluation of each branch of the tree to find the most convenient immediate move, evaluation that may include not only the eventual end state of the board at the ends of that branch of the trees, but the likelihood of each of the opponent's moves. ①

Before these solutions can be generated, searched, reduced and evaluated, some symbols and operations must be defined; in other words, a *representation* of the problem must be designed. For example, a chess-playing system may operate on descriptions of the state of the chess board, that is, the position of each of the pieces; the operations that can be performed on these descriptions would include valid piece movements, or functions that measure the desirability of having a piece in a certain position relative to other pieces. Other symbols that may be involved could include standard moves, such as the classical chess opening moves, in such a way that the system can easily recognise when the opponent has performed such a move, and know what the consequences of that move are without elaborate analysis.

In spite of the spectacular performance that such systems exhibit – few human chess players can outperform the best chess playing programs today – these efforts were in a way disappointing because of the extreme narrow focus of the results. While some of the searching and problem reduction techniques developed as a consequence of that research are applicable to a large class of problems, the problem representation aspects were extremely case-dependent: the symbols and operations developed to solve chess moves are of little or no value outside that specific problem domain.

This frustration let, in the late sixties and early seventies, to a fury of efforts to find more universal problem representations; ideas such as "problem solving" systems and "logic reasoning" systems seemed attainable at the time. At one time work actually began on a "General Purpose Problem Solver" system, with no clear limitations on what kind of problems it could solve. When it became apparent that finding truly domain-independent means of representing problems was a little too difficult, researchers then directed their efforts to more restricted, but still relatively generic problems, for example proving mathematical theorems or automatic computer programming.

Also at this time, and perhaps influenced by the success of the early game-playing programs, some individuals began to make exaggerated claims about the practical possibilities of A. I. systems. Actually, this had already happened before, even before the term "Artificial Intelligence" had been coined. Grossly unrealistic estimates of the potential of computers to perform "intelligent" functions – whatever those may be – were common during the early days of electronic computers, as exemplified in the contemporary label "electronic brain".

While it helped sell some of the early work in computers, it became apparent to many that such overselling would, in the long run, be detrimental to the growing computer industry. As a matter of fact, IBM, the commercial leader in the field, established a rigorous internal and external program to dispel the "electronic brain" concept from their own employees and from their customers, an effort that culminated with the coining of the word "ordinateur" for use in French-speaking IBM markets. My reason for bringing to light this incident is that I believe that we are today witnessing a repeat of the same phenomenon: some recent successes, particularly the development of A. I.-oriented hardware, and

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[1] The circled numbers in the right-hand margin reference the viewgraphs that were used in the presentation, which can be found at the end of the text.

the commercialization of some A. I. products, have led to a new round of overselling which we must avoid very carefully: while A. I. technology is promising, it is certainly not the solution to all our problems.

But back to our history: While attempts to build generic problem solving system were invariably unsuccessful, researchers discovered in the early seventies that once a problem was represented by means of computer-manipulable symbols, it was an easy task to store individual ad-hoc knowledge about that problem, much in the same way as standard moves could be memorized in a chess-playing program. And, while standard moves are but a small portion of the knowledge required to play a good game of chess, there are other areas where it constitutes most, if not all, of the knowledge.

Consider, for example, the problem of integrating mathematical expressions; once a student learns the basic concept of what an integral is, the problem is really reduced to learning a very large number of "standard" integrals, such as cos(x) being the integral of sin(x), and being able to recognize patterns in the problem that match one of the known standard integrals. Well, once the symbols and operations required to store and manipulate mathematical functions in the computer is developed, one can store hundreds, even thousands of standard integrals and integration techniques. In the most famous and successful system of this kind, M.I.T.'s MACSYMA program, scores of computer scientists, logicians, and mathematicians have contributed an enormous number of rules describing not only how to integrate, but also how to perform a wide range of mathematical operations.

Let me show you a typical use of MACSYMA. This slide was produced directly from my terminal screen in our A. I. computer complex. Lines with numbers beginning with the letter C are my inputs, while ② lines identified with the letter D are the outputs from MACSYMA. I begin this example by typing in an equation in a form which looks very much like FORTRAN. Notice, however, that MACSYMA displays my input back in a form that resembles the way one would write this equation on a blackboard; this is possible because the representation of that equation used in MACSYMA has concepts such as power and denominator.

I then ask MACSYMA to "solve" for the variable Y in that equation; what happens next is that MACSYMA recognizes a binomial equation pattern in that expression, and invokes the rules to solve such equations that we all learned in High School. If, on the other hand, we ask MACSYMA to integrate the right-hand side of that equation, it will recognize a *polynomial* pattern, and invoke the classical polynomial integration rules. While I could do that myself, I would be hard pressed to integrate the expression shown in the next slide, which involves knowing some rather exotic rules of integration. ③ I use MACSYMA frequently in my work, especially to manipulate rotation matrices that transform, for example, position vectors in radar site coordinates to mosaic-relative coordinates. This kind of system which is composed of an internal representation of a domain, a set of rules representing *knowledge* in that domain, and a set of commands that allow the user to invoke the appropriate rule without knowing the details of that rule is called a "knowldege-based system", or, more precisely, a "stored-knowledge" system: the computer program has the knowledge, but does not know when and how to apply it unless specifically instructed by the user.

The indisputable success of these "stored-knowledge" systems, coupled with the failure of totally generic "problem-solving" or "thinking" programs, resulted in the "Expert System" concept. Like the stored knowledge system, an "Expert System" operates with symbols and operations representing knowledge in a particular field, and sets of pre-stored "rules" which embody knowledge, just like the integration rules in MACSYMA. The Expert System, however, has two additional ingredients: first, the capability of chaining the given rules, perhaps with the help of "intermediate results", to reach conclusions that are not covered by any single rule; and, second, logic to direct both the invocation of the rules and the chaining of simple rules to achieve a specific objective.

Perhaps the best way to understand the notion of "Expert System" is to observe one in operation; in the next few slides, I will show you a typical conversation with perhaps the most famous, or successful, of all expert systems: the MYCIN bacterial infection diagnostic program. In the MYCIN system, a moderately large set of rules (about a hundred) are used to store knowledge about bacterial infections. But whereas in MACSYMA the rules were scanned to see if one of them satisfied the request typed by the user (e.g., integrate a given expression), MYCIN rules are automatically activated in a complex way by a logic in the program called the “inference engine”, whose built-in goal is fixed: to determine the best antibiotic treatment for a patient whose infection is not precisely known.

To understand why MYCIN behaves the way it does, indeed to understand the importance of the development of MYCIN, we have to review briefly what kind of problem it is solving. There are thousands of bacteria that can cause infections in humans, and hundreds of available antibiotic drugs that act specifically on a bacteria, or groups of bacteria, while having more or less desirable side effects. If the identity of the bacteria causing a patient's infection were to be known, a very precise antibiotic treatment could be prescribed. Unfortunately, full identification of a bacteria from a culture requires from a few days to a few weeks, while antibiotic treatment must begin immediately. Thus, treatment is begun with only sketchy data on what kind of bacteria is involved – usually a two to three hour culture yielding only very basic information about the bacteria, not its precise identity.

The way MYCIN achieves this objective is by assuming a very large number of possible alternatives, and then asking the user to provide information that it can use to eliminate as many alternatives as possible, until all the information is exhausted. This technique is known as *backwards-chaining* the rules.

④ The conversation shown in these slides is a little long, but I hope you will find it interesting; MYCIN's questions are preceded by a number, while the user's answers are preceded by three asterisks. After the usual basic questions about the patient, MYCIN, checks in question (4) that the basic operating premise, that is, the existence of an infection, is indeed true (I guess that if one were to answer no to that question MYCIN would simply say Oh, well, goodbye, then).

At the very beginning of the conversation, MACSYMA printed the label `PATIENT-1`; after question (4), it prints the label `INFECTION-1`; these labels are an indication of the *context* of the conversation. When we humans exchange information verbally, we implicitly establish a context in which indefinite articles such as“it” or “he” have a unique meaning. Although MYCIN does not *understand* English, it always has a *current context*, or implicit object of inquiry which begins with the patient, switches to the first infection (for that patient), and then may change to an organism, to a culture, change back to the patient, and so on.

⑤ After establishing that the type of infection is known, so that a series of questions leading to the identification of the type or possible types of infection is not necessary, MYCIN then proceeds to find out what laboratory information has been obtained on the organism or organisms producing the infection. ⑥ Answers to a question, including the answer “don't know”, dynamically modify the sequence of successive questions. Note also that the user's answers can be followed by a number in parenthesis, such as in question 13; this indicates the degree of confidence that the user has in that piece of information, with 1 indicating absolute certainty, and 0 being equivalent to a don't know answer.

⑦ After about forty or so questions, MYCIN is ready to display a conclusion; perhaps it is satisfied that this conclusion has a low enough uncertainty factor, or, more likely, the user has begun to answer “I don't know” to so many questions that MYCIN decided that to give up asking. In any case, MYCIN displays, first, its conclusions regarding the possible identity of the organism causing the infection. As you can see, it is not a single conclusion, but rather six. ⑧ Next, after three additional questions, MYCIN proceeds to issue a “preferred treatment”, preferred in that there may be other treatments covering the same set of bacterial infections, and which may be preferable to the user for reasons that MYCIN cannot handle (for example, local availability).

⑨ The next slide shows the form of a typical MYCIN rule; on the top of the slide is the text of the 50th rule, as stored in MYCIN, while a comment in English, at the bottom of the slide, explains the meaning of the rule (for the benefit of us humans). The rule has two parts: a *premise* and a *conclusion.*

If the premise is true, then the conclusion is true, much like an *if - then* statement in a traditional programming language such as FORTRAN. A program using this kind of rules is sometimes called a *production system*.

The premise is in itself composed of the boolean, or logical, combination of three *clauses*; each clause in itself consists of a *predicate* – a statement that may or may not be true – relating an *attribute* of an *object* to a *value*. For example, in the second clause of rule 50's premise, `MEMBF` (meaning "a member of") is the predicate, `CNTXT` is the object – actually, this stands for "the current context, whatever it may be" – `SITE` is the attribute, and `STERILSITES` is the value with respect to which that object's attribute must satisfy the predicate. This clause would be true if the value of the `SITE` attribute of the current context is a member of `STERILSITES` (presumably a list of values).

The action part of Rule 50 consists simply of the identifier `CONCLUDE` followed by a statement of value of an object's attribute, possibly followed by a certainty index: here, the rule affirms that the `IDENT` attribute of the context is `BACTEROIDES` with a certainty of 0.7. Note that this fact could have been established by the user if he had answered positively question number 9, which asked "Enter the identity of organism-1". MYCIN rules are triggered by values of attributes, and these values can be established either by user's answers or by rules' conclusions. Indeed, MYCIN's backwards chaining logic determines which questions to ask the user by determining which rules, if triggered, would restrict the potential conclusions the most.

I find a demonstration of MYCIN an impressive experience, but perhaps this is due to the impressive medical terms used, rather than the computer's operation. My medical friends tell me that it impresses them too, but then I suspect that perhaps it is the computer that impresses them. Nevertheless, I am convinced that Expert System technology can be of considerable value, but only if applied to a problem for which an Expert System is honestly the best tool to use.

## 3. ATC APPLICATIONS OF A. I. TECHNOLOGY

This overview of the world of Artificial Intelligence has been, by necessity, very brief. It has not covered, for instance, any of the work done in natural language processing, that is, the analysis of human language – written or oral – to extract specific information; I have not covered speech synthesis and recognition – a different problem than that of understanding natural language; I have not covered robotics, the discipline that deals with mechanical manipulators and touch sensors; finally, I will only mention vision and image recognition, even though I believe there may be an opportunity for ATC applications of artificial vision.

After having explained what A. I. is, it seems that in order to make justice to the title of this talk we should also briefly mention what we mean by ATC. By Air Traffic Control we do not mean exclusively the activity of the man or women behind the radar screen issuing vectors and clearances to aircraft and looking out for conflicts; we very specifically include all the activity that, combined, makes for a safe and efficient ATC system, such as planning the command and control structure of the system – that is, determining when and where information is transmitted, and when and where decisions are made – or selecting the set of airways that will constitute the preferential routes from two busy terminal areas in a particular complex weather situation. As you will see, the possibilities for useful applications of A. I. technology to the world of ATC go well beyond the radar controller's screen.

Some of the technologies of Artificial Intelligence can be of quite immediate application; others may have to wait five, ten, or even twenty years before they can be seriously considered. I will try to be as broad and comprehensive as I can, so I will mention both short-term and long-term applications. I would like. however, to divide these immediate and future applications in a different way, namely two groups which I call "visible" and "invisible".

Invisible applications are those where the A. I. component is hidden from the final user of the ATC product or system. Perhaps A. I. technology was used in the design, development or implementation of the system for economic reasons, or perhaps it is the only way in which to mechanize a certain function, but as far as the user is concerned, it is just another computer program.

In a visible application, on the other hand, the particular behavior of an A. I. product – as typified in the MYCIN example – is an essential part of the usefulness of the tool, and the user must be prepared and trained to use it in this way. In the invisible category I would like to mention symbolic programming, experimental simulation, radar tracking algorithms, and procedure generation. In the visible category I would like to propose a theoretical flow oriented command and control structure, an expert system to help select runway configurations, two very similar applications of visual scene recognition, and the "controller's assistant" concept.

"What?" you will say: "he is not going to talk about applications of voice recognition?". Well, I am sorry to disappoint you, but I am not. About the only application I can foresee for this technology is the simulation of pilots' voices – and ears –in a real time Air Traffic Control simulation, and I am afraid that the available technology is not capable of doing even this. At the present time, voice recognition and synthesis seems to be more of a solution looking for a problem, that a solution to an existing problem. Actually, I would be delighted to be proven wrong so I can have an excuse to buy a new voice recognition system for my lab.

## 4. ARTIFICIAL INTELLIGENCE AND THE MANAGEMENT OF COMPLEXITY

The history of aeronautical technology has always characterized by "barriers", or measures of performance that were considered unattainable: transoceanic flight, stratospheric flight, blind flying, the sound barrier, the heat barrier, space. One by one these "barriers" have been conquered. I believe that the current barrier, the one performance limit we must conquer today, is the "complexity" barrier. Consider this: Charles Lindberg's aircraft, the Spirit of St. Louis, required 850 man-hours of engineering effort to design; the Lockheed C5A Galaxy transport jet took 49 *million* man-hours to design. As aircraft become more complex, and as the relationships between aerodynamics, propulsion, avionics, and even radar signature become more and more interrelated in determining the performance of the aircraft, this complexity, and the cost of designing it, will become greater and greater.

Nowhere is this more dramatic than in present and future Air Traffic Control systems. The U.S. ATC system has already been dubbed "the most complex man-machine system in the world"; indeed, its complexity has reached a point where nobody quite knows how the entire system operates, and it is becoming more and more difficult to estimate what effect on the entire system the introduction of a new component, such as direct routings, will have. Even something as simple and as localised as the minimum safe runway lateral separation for simultaneous instrument approaches requires a tremendous amount of engineering and analysis to determine, since it involves the interaction between radar performance, flight procedures, aircraft dynamics, and aircrew performance.

Is there a limit to this complexity? Will we reach a maximum complexity in aircraft and ATC systems beyond which it will be impossible for us to determine if the system will work properly?

Another area where the cost of this complexity in quite evident is computer software; it is a well established fact that the cost of developing a software system is not proportional to the sise of the system: "two programmers can do in nine months what any of them could do in twelve months" is the popular proverb. A more detailed analysis of the additional costs incurred when a large software project is partitioned in N smaller components is N to the one and one-half power, and this, coupled with the decreasing cost of computer hardware, has resulted in a reversal of the relative importance of hardware and software costs: whereas fifteen years ago, hardware costs for a large system were typically then times larger than software costs, today it is software which is about ten times more expensive than hardware for a typical command and control system.

Artificial Intelligence researchers discovered the software complexity barrier very early, and, with the freedom possible in the academic and research environment developed a number of tools and techniques to manage this complexity far more effective than those developed by the industrial community, subject to the demands of daily business. While the latter tried to manage software complexity by building more complex tools, therefore adding to complexity – I am referring here to the Ada language and all the tools that have been developed around it – the universities and research laboratories have developed Lisp machines and Icon-based interfaces: they attack complexity by developing simpler tools, not more complex ones.

The differences in programming productivity are tremendous: while the industry standard for fully developed, tested and documented code ranges between 1200 and 2000 lines of code per man-year, project-wide averages of 20000 to 50000 lines are not uncommon in Artificial Intelligence projects. In addition to the simple increase in single-programmer productivity, this difference is compounded by the reduction in the number of individual pieces in which a large project must be subdivided in order to meet the required schedule (the "n to the one-and-a half power" law), with overall differences in software cost of up to 100 to 1, for the same resulting software functionality.

⑩ The reason for this difference is actually quite simple: programming is nothing more than the translation of the original functional specifications of the system to be designed into the simpler elements that can be executed in a computer; in the early days, these were individual bits, representing either data or instructions, so that the entire translation process had to be performed by the human programmer. Next came the "assembler" or "machine languages" which, while operating with the same machine-level elements, at least allowed the programmer to refer to them by names and symbols, rather than by anonymous numbers. The advent of the so-called "high-order languages" raised the interface to the level of vectors, arrays, strings and passive data structures, and produced what appeared to be a miraculous increase in programming productivity.

High-order languages, even in their most complex form such as Ada, are still rooted in the Von Neumann concept of the computer as a sequential executor of instructions. Code and data, for example, are two distinct and unmixable elements, linkable only through the process of compilation. By comparison, symbolic computation removes itself one step further from the details of hardware, and allows truly abstract concepts to be represented and manipulated on a computer. Probably the most spectacular consequence of this increased level of abstraction is that the program itself, or "code" becomes simply one more abstraction, and thus can be *directly* manipulated by a program without the compilation or interpretation barrier of high-order languages.

And this is only the beginning; A. I. research is fast advancing in the direction of "declarative programming", languages – or, rather, programming models – that allow the user to state the functional specification for a computer system in extremely abstract terms without having to specify, for instance, the sequence in which operations have to be performed to arrive at the desired effect. These languages, while still many years away, may make Lisp look as mechanical and complex as high-order languages look in comparison to Lisp.

It is interesting to observe that while the attempts to build an "automatic programming system" during the early seventies were dismal failures, the same results are begin arrived at by a diametrically opposite route: instead of a very-high level program that transforms any program specification to the detailed instructions that computer hardware requires, we are seeing computer hardware and software that operate at higher and higher levels of abstraction: a "bottom-up" approach, rather than the "top-down" approach of the automatic programming concept.

Of course, nothing comes free; this increase in the level of abstraction at which the machine interfaces with the human programmer entails an inevitable increase in the processing power required in hardware. But one should not look at this increase as "inefficiency" or "overhead"; in fact, this additional processing is performing an extremely useful function, namely the translation process from abstraction to machine bits and back, of both code and data. Therefore, will have to learn to accept much higher computer processing requirements as a natural by-product of our increase in complexity; but do not worry: the continuing decline in the cost of processing, or, if you wish, the increasing performance of computer hardware will make it more palatable. The important point to consider is that the computer technology – both hardware and software – used today by Artificial Intelligence researchers may become the only economical way of implementing very complex software systems in the near future.

## 5. RESEARCH SIMULATION TECHNOLOGY

Leaving behind the world of computer software, we find that some of the same problems that plague builders of large software systems also haunt designers of large HUMAN systems; even if the Air Traffic Control system used no computers at all, the flow of information, and the distribution of decision-making authority makes the system look very much like a gigantic computer, with procedures, rules, regulations, and letters of agreement being its "program".

We have long passed the stage where the effects of major changes in procedures or technology can be evaluated effectively by simple analysis: simulation becomes the ultimate evaluation and verification tool. Unfortunately, building and running a sufficiently good simulation of a very complex system can extremely costly.

Consider the differences between an aircraft simulator and, for example, the simulation of an advanced ATC controller station of the year 2000. While the basic principles of aerodynamics, structures, propulsion and so on cannot change radically from now to the year 2000, the same cannot be said – at least in principle – of Air Traffic procedures: there are few physical limitations to what can be displayed on a futuristic controller's screen. So whereas the aircraft simulation can count on a number of essential fixed elements no matter what the configuration of the experiment may be, the same cannot be said of an Air Traffic Control systems simulation.

One of the "secondary skills" that the Flight Transportation Laboratory has had to acquire as a requisite to perform high-quality research in Air Traffic Control is the design, building and running of large scale simulations of the Air Traffic Control environment. We are now beginning the design of our fifth ATC simulator, which will use what we consider is the "third generation" of simulation technology, a technology based on a combination of symbolic computation and object-oriented programming, a technology which, although now part of the standard vocabulary of modern computer science, was developed, and is heavily used by, the Artificial Intelligence community.

The traditional way of designing, implementing, and using large system simulators was this: a detailed specification was drawn of the "fixed" part of the system, that is, the part that is not expected to change from one experiment to another. Next, the user defined some bounds on the kind of experiments that would be run on the simulator. The simulator designer then would convert the fixed part of the specification to detailed formulations of the "core" of the sim, which would include generation of large amounts of data that could be used to feed the expected experiments. Also, the behavior of the core system would be determined, as much as possible, by parameters that could be read from a data file a simulation initialisation time, so that the core could be tailored as much as possible to the particular experiment that is to be run.

To put all these words in perspective, let us consider a "typical" Air Traffic Control research simulation. The core would probably consist of models of the dynamics of the aircraft – popularly known as "targets", since most classical ATC seems were developed from radar simulators; also included in the core would be simple radar models, a simple controller display screen, tools to measure "performance" of the system (for example aircraft minimum separation), and the tools to allow the experimenter to control the experiment: start and stop the sim, create and destroy targets, induce faults, etc.

Now the trouble begins: what should we include in the aircraft models? Well, since a future ATC system is likely to use the Discrete Address Beacon System – now called "Mode S" – as opposed to the traditional Mode C transponder, we should probably include it in the aircraft model, as well as on the radar model, since it may have back-to-back antennas to double the interrogation rate. How about direct, off-route navigation capability? Microwave Landing System? Digital downlink? Now, certain experiments are likely to involve weather avoidance; should we build models for weather patterns, or at least the presence of weather data on the controller's screen? The list can go on indefinitely.

Suppose we have the resources to program most of the features that we expect could be required on most experiments. Certainly not all experiments are going to require all of these features. But never mind, we can enable or disable any of these models by means of flags in the initialization file, so only those components that are actually required in an experiment will run.

But now, suppose somebody wishes to run an experiment to determine the best way in which Central Flow Control should interface with the Traffic Management Unit at a Center! Well, now we are out of luck, because we certainly cannot afford to simulate hundreds of aircraft – and we need that many to simulate the actions of flow control – at that level of detail. Indeed, we probably do not want to simulate flow control operations in real time, but faster than real time. Oh well, you can say, that is not fair! We have the wrong level of detail simulator to analyze flow control problems! That, of course, is absolutely correct: you need a *different* simulator to analyze that problem, one where the position of each individual aircraft is not important, but only the number of aircraft entering and departing each sector.

But let us assume that we have a problem that does require the real-time simulation of the position of each individual aircraft; let us assume that we wish to evaluate the benefits to the controller of a conflict alerting algorithm. Certainly that algorithm was not included in the detailed specifications of the core system around which the simulator was build, so it will have to be coded specifically for this experiment. Where will the data required by this algorithm come from? Most likely from specific slots in some FORTRAN common block. This means that this detailed implementation data will have to be carefully documented and controlled; it also means that for each experimenter, for each algorithm designer, there will have to be an army of programmers dedicated to interfacing the new algorithm with the simulator. Even if the cost of this programming were acceptable, the time required to prepare an experiment would run in the weeks, if not in the months.

The alternative to this traditional approach is to build not a "core" simulator, and an array of ad-hoc extensions for each new experiment to be run, but rather a "kit" of building blocks with which a customised simulation can be built in a very short period of time. In other words, we not only accept, but actually encourage the notion that a new simulation will have to be built for each new experiment in Air Traffic Control technology. ⑪

The key to this approach is the level of abstraction of these building blocks. Using symbolic programming techniques, it is possible to build blocks such as "VOR", "Aircraft", "Random Aircraft Generation Point" "Airport Runway", "Airway Intersection", "Radar", "Display Screen", and the like. Moreover, there can be many different types of these blocks, not only in terms of their performance parameters – you can do this in FORTRAN with initialisation files – but even in the level of detail being simulated. ⑫

For example, the Flight Transportation Laboratory is currently designing a "building block kit" which will allow the experimenter to intermix three very different levels of simulation at the same time: a Level I, where the smallest geographic unit represented is a control area, say several sectors large, and aircraft ⑬ dynamics consist only in movements from an area to an adjacent area. At this level of detail, the entire continental U.S. could be modeled, with some 2000 aircraft, with very little effort required to set up the experiment. A Level II would look into the actual geometry of the airway structure, as well as direct routings, and be able to model individual sectors. At this level of detail, the position of each individual aircraft along an airway or along its direct route would be modeled, but not, for example, the effects of individual radar vectoring. The maximum number of sectors that one would like to model this way is probably ten or fifteen, with a total of one to two hundred aircraft, enough to analyse problems relating to the communications and handoffs between two centers. Finally, Level III of simulation detail would look at individual aircraft dynamics and the performance of radar sensors, and would be the level of detail at which to look at problems such as simultaneous instrument arrivals to closely-spaced parallel runways, or the sector-to-sector interactions for a maximum of, say, three sectors and thirty or forty aircraft.

This "building block kit" would then include not only three levels of airspace models and three levels of aircraft models, but also different display formats for each level. The important feature of this approach is the possibility, if designed correctly, to run a simulation where the entire country is modeled with Level I elements, except for two centers, which are modeled with Level II elements, and have within these two centers two or three sectors modeled with Level III elements!

Object-oriented and symbolic technology are capable of solving the problem of interfacing these rather dissimilar objects together. Consider a flow control algorithm that wants to know how many aircraft are in a certain area, the smallest Level I unit of airspace. In traditional programming, the programmer would have to know the location of that number in whatever data structure contains that information for a Level I area, but would probably have to write a subroutine to obtain that information from a Level II center, since it would have to add all the aircraft in each of that center's sectors. With object-oriented programming, the burden of providing any information about an object is shifted from the seeker of the information to the supplier of the information.

The technique in question is called "message passing"; each object in the "kit" is known to respond to a certain number of requests, or "messages". These requests can either ask for information about the object, or ask that the object perform some action that has a "side effect", such as displaying a symbol on a screen. All the interactions between objects must be through these "publicly advertised" messages. Part of the effort required in designing such a simulation is to define what kinds of messages should each object be required to handle.

Once this is decided, though, the task of inter-object communication is enormously reduced; if both Level I areas and Level II centers are required to reply to the message "how many aircraft do you have now", it does not matter to the object requesting the data whether this data is obtained by simply looking it up somewhere, or by laborious computation: it simply is returned in response to the message. If the internal makeup of an object must be modified – say, in response to the requirements of a new experiment – only its way of handling its incoming messages must be modified, whereas in the traditional technology every object that could possibly interact with the modified object would have to be modified as a consequence of this change.

The development of this simulation architecture is, in my own opinion, the most exciting ATC-related project at the Flight Transportation Laboratory in the last decade. If successful – and there are a number of major technological obstacles still to overcome – it may enable for the first time the testing and evaluation of truly advanced ATC concepts in a sufficiently realistic environment, at reasonable cost.

The concept of building a real-time ATC simulation "on the fly" based on software building blocks as I just described has been demonstrated at the Flight Transportation Laboratory, where a full scale Level III simulator using this technique is in daily use. The largest technology risk associated with this simulation is related to its hardware; in addition to the building-block software approach described, it is designed around a building-block *hardware* architecture; the same message-based interaction technique that allows different kinds of objects to interface in a homogeneous manner will also allow these objects – and the functionality they carry – to reside in different processors, with some limitations, so that the exact number of processors available to run the simulation is invisible to the software, although, of course, the resulting performance will be *very* visible to the user.

This will also allow incremental growth in the capabilities of the simulator, as more processors and display hardware are added without the need for software re-coding, but is dependent on very recent, and still untried advances in symbolic computation hardware.

# 6. AN EXPERT SYSTEM FOR RUNWAY CONFIGURATION MANAGEMENT

Curiously, there are fewer opportunities for "classical" expert systems such as MYCIN in Air Traffic Control than one might expect. Indeed, there a few circumstances where *accumulated knowledge*, as opposed to skill or ability, determine the performance of a control function.

Perhaps one of the most promising short-term applications of classical expert systems may be to the problem of runway configuration management, that is, the selection of a what runway configuration to use under changing weather and flow conditions. Complex airports, such as Chicago, or the New York City Metroplex, have hundreds of possible runway and approach configurations. The problem consists in selecting which configuration to use, and, more particularly, selecting *when* to perform a configuration change: the relative timing of the arrival of a front at the airport terminal area with respect to the peak traffic hour may make a difference as to whether the runway configuration change should be performed in advance, or delayed with respect to the weather-optimum time. Moreover, weather at *other* airports may affect the normal traffic pattern at an airport so that, for example, a snow storm approaching the Boston area from a westerly direction requires a different runway configuration change strategy than one approaching from the northwest, since the former will hit New York before Boston, therefore causing potential diversion of traffic from the NYC area.

This *simultaneous consideration* of multiple contradicting factors, some of which may be the result of many years of experience and observation at the station in question, lends itself ideally to mechanization as an expert system. Indeed, FTL is developing such an Expert System, under the code name "Tower Chief". This name was selected to bring to mind the notion that the Tower Chief is usually the senior – therefore the most experienced – controller in that facility, and therefore would be the ideal person to make runway configuration decisions at all times, not just when he is the actual shift supervisor. By capturing "his" expertise, the expert system would make available to any supervisor having to make such decisions the expertise and accumulated knowledge of the senior person.

Actually, such an expert system would be capable of storing knowledge and associations furnished by a number of individuals, and therefore be of use to the Tower Chief himself, specially in its ability to be *comprehensive* in examining all the knowledge elements pertinent to the current state of affairs. On the other hand, I dislike the name "Tower Chief", since, in addition to the concept of wisdom and experience, it also calls to mind the concept of authority, or responsibility. There is therefore the danger of concluding that such an expert system, by virtue of its superior data base, is able to make superior decisions than a human in this situation. This is clearly not so. In fact, beyond the assurance that the expert system has systematically tested all the knowledge contained in the data base, the greatest benefit that the shift supervisor can derive from the use of tower chief is not the final conclusion or recommendation that it may make regarding the runway configuration changes to select, but rather its capability to display the logical process that lead to that conclusion. This display can be used not only to help make a final decision, but also to enrich both the expert system's and the human's knowledge base; therefore, I would have preferred to title this project "supervisor's consultant", but it is a little late for this, so I will continue to call it "Tower Chief".

Some technical problems must be resolved before rules and knowledge can begin to enter a Tower Chief prototype system. As with all knowledge-based systems, expert or not, the work begins with the construction of logic abstractions capable of representing, both to a computer and its user, the elements of knowledge in the particular field; for Tower Chief, these may be "runway", "prevalent winds" "primary flow direction" etc. etc. with, again, both data *and* functionality being associated with these abstractions. This is the *knowledge engineering* phase, and is now under active development for Tower Chief at FTL.

Simultaneously with the knowledge engineering phase, an "Expert System systems design" must be carried out. This is the design of the process by means of which the abstractions will be entered, searched, activated, processed, and displayed in the operation of the expert system. There are a number of "classical" methodologies, such as "forward chaining", where as many of the rules as may possibly be activated given the established facts are invoked, until all the rules have been used, and MYCIN's "backwards chaining", where a number of hypothesis are postulated and tested by means of the rules, until as many of them as possible have been weeded out. Other classical techniques address the method of incorporating rules into the knowledge base, requesting specific data items as the hypothesis tree is traversed to reduce the number of branches that must be explored, etc. This collection of techniques, and the software used to implement them are referred to as "expert system cores".

A small but growing industry of "pre-fabricated" expert system cores offers a large number of more or less off the shelf software systems. These cores consist of a general-purpose structure for representing knowledge, and the "inference engine" or logic that drives activation of the rules to achieve the final objective. Along with these features, some of these systems also come equipped with fabulous claims about the speed and ease with which useful expert systems can be built around them.

Unfortunately, these claims are usually exaggerated for two reasons: first, because experience has shown that rule-processing procedures are much less universal than previously thought; second, because even if an existing core is adequate to perform the rule processing required in a particular problem, a significant knowledge engineering effort is usually required to cast the particular knowledge relevant to the problem in the forms required by the expert system core.

Tower Chief is the second ATC-oriented prototype expert system developed at FTL. The first – known simply as Rule System One, or RS-1 – was only an experimental system in which conventional algorithms could be re-implemented as rules, and was developed to gain familiarity with expert system techniques, and not to demonstrate any useful function. RS-1 showed us, for example, that ATC problems are particularly ill-suited for pre-fabricated expert system cores. In RS-1, data, or rather, assertions about the objects known to the system, arrived in time-sequenced frames, corresponding to entire revolutions of an terminal radar antenna; thus the "assertion base" – the data base of statements asserted to be true about the objects – was continually evolved; moreover, rules may refer not only to current assertions, but also to past assertions, or even *changes* in assertion, as for instance: "If aircraft-1 appears to be on a base leg, and it was previously affirmed to be on final, something is wrong". Among the interesting consequences of the RS-1 work, we found that the concept of "past", as applied to computer implementations of knowledge, is more complex than previously thought.

Symbolic computaion has tought us that the concept of "equality" is more complex than the simple "equality of numerical values" of FORTRAN; for example, a simple chair and an armchair are clearly not "equal" , while two identical armchairs are, to a certain degree, "equal", although they two *two* different chairs – two different notions of equality. Similarly, we have two different notions of "past": suppose, for example, a rule which estimates the general direction of an aircraft track; this rule may ask the assertion base for the *previous* heading of the aircraft in order to compare it with the current heading. But suppose that, during the previous four-second revolution of the antenna, insufficient valid transponder hits were received and a missed reply was declared for that target during that antenna revolution; what should be answered to the question "what is the previous target data?" One possibility is to answer "not known", since there was no reply on that antenna pass; but another is to return the target data for the last antenna pass during which there *was* valid data. In a way, both are "previous" data, but the answers may be quite different.

The consequence is, of course, that there are (at least) two different "pasts", one relating to the sequence of known data, independently of the time at which it was asserted, and another relating to a sequence of instants of time. Such a feature was not available in "off the shelf" cores at the time the RS-1 effort was started.

In addition to this "passage-of-time" problem, Tower Chief will also be subject to three more time related problems: first, the elements of knowledge that Tower Chief will handle will have themselves a time component, similar, but more complex, than the time-related questions asked by MYCIN.

Second, the goal of this expert system is really a program, or timed sequence of runway configuration changes, so time is one of the components of the answer, as well as of the data used to arrive at the answer; nobody has had any significant experience in designing expert system that deal with time as one of the parameters of the goal.

Third, – and this is a problem faced by all Expert Systems whose answer is required in real time – the search for answers may be terminated by the time available, rather than by exhaustion of the search, as in MYCIN, where the time required to arrive at the answer is not really important, as long as it is reasonable. There is little experience about time-constrained expert system performance; indeed, we already know that expert systems share with some Operation Research methods the property that, while monotonic, the rate of improvement of the answer may vary widely with time: in some cases, an excellent answer may be arrived at very quickly, with only marginal improvements afterwards; in other cases, the bulk of the solution improvement may only be achieved at the very end of the search, so that an early termination may produce a very unsatisfactory answer. We don't know at this time if the amount of processing required by Tower Chief will be such that time-terminated processing will be required; if it is, its performance may depend on new developments in solution search techniques which guarantee uniform solution improvement with time. As an aside, one of the methods that have been proposed to achieve this uniformity involves the intentional randomization of the search procedure, in a "Monte Carlo" like process.

## 7. TWO SIMPLE APPLICATIONS OF MECHANICAL VISION IN ATC

An entire field of research in Artificial Intelligence is that of visual scene recognition, that is, the processing of raw data from, say, a television camera or other means of converting visual information into bits, with the purpose of identifying objects, positions, three-dimensional shape, and even higher-order relationships, such as attachment between objects or their constituent materials.

At first glance there would seem to be no obvious application of this "robot vision" capability in Air Traffic Control, unless one wished to build a robot tower controller or a robot pilot. Actually, there are two very good possibilities, one on the ground, and one in the air.

A useful ground system based on mechanical vision and scene recognition would be a low cost, totally passive LIDAR, or Light-based Radar. Such a system would consist of two, perhaps three Television cameras mounted on fast remote-controlled tilting and panning heads, and equipped with fast zoom lenses. Controlled by a computer with visual recognition software, this system could act as a "VFR radar" in congested small general aviation airports, those airports, such as my own home base in Bedford Massachusetts, whose traffic density changes from being higher than that of Heathrow during fine VFR conditions, to practically nothing as the weather becomes IFR. Visually scanning for aircraft, this system could present to the tower local controller a plan view display of the aircraft within the airport's traffic area.

In its simplest form, this system would periodically scan the horison surrounding the airport and create a visual "map" of the fixed features around the cameras: trees, buildings, hills. Some of these features may change periodically, such as the foliage of the trees, but just as in a modern radar's clutter map, they can be immediately recognized by their very, very slow rate of change.

Real scene recognition begins with slow, but really dynamic objects, such as clouds and birds. Clouds have such a characteristic texture, size, and speed that it should be trivial to separate them from aircraft targets. How can this system distinguish a bird at five hundred meters from a light airplane at five kilometers? One possibility is radial velocity: the bird at five hundred meters can faster across the camera's field of view than a similar-sized aircraft target.

Now, if the bird happens to be flying towards the camera, then the computer can zoom in to increase the level of detail of that target, and real shape recognition can occur. Military research in the recognition of surface ships by their shape has shown that this technology is capable of differentiating even the minute differences between sister ships. It should not be very difficult for this proposed system to determine not just the difference between a bird and an aircraft, but even the type of aircraft, its registration number, and, by determining the attitude of the aircraft, its heading, course, altitude, and descent rate.

In addition to acquiring all this information, the system has some unusual potential for presenting the information to the controller: for instance, instead of the usual bars we are accustomed to in high-intensity radar displays, we could have a small picture of the actual aircraft, in color, obtained by the system's cameras, and processed by the computer so that at any time in that aircraft's flight, that picture should look just like what the controller should see with his binoculars were he to look for that aircraft.

Now we have a system that not only is more sensitive than a human controller in detecting and processing visual targets, but may even provide him with additional information about the target that a conventional radar certainly could not. And being only software, it is a cheap system to produce in large numbers, so as to offset its probably large software development cost.

While the hardware required to process the amount of visual information that such a system would need is not very far in the future – say, five to ten years – here is another system that will probably have to wait a little longer for the needed hardware capability to develop. Take the airport visual surveillance system, and mount it on an aircraft, using wide field-of-view fixed-focus lenses and extremely high density imaging devices. Program the scene recognition system to look out for visual targets and deduce its trajectory with respect to the own aircraft. You have then created a visual collision avoidance system with the same or better performance than a fully alert human crew member.

## 8. AN ABSTRACT CONCEPT OF FLOW CONTROL

The next concept in Air Traffic Control that I would like to present to you is not a "gadget" like Tower Chief or the visual radar, but actually a concept. It is related to Artificial Intelligence because it is the result of building abstract representations of knowledge, capable of being implemented on a computer; but also independent of any computer implementation. Indeed, they could very well be implemented as procedures, with humans performing all the information handling and decision making.

These abstractions are models of how a flow of aircraft could be regulated by control elements that interact only with their neighbors; at what level this flow control would be carried out is immaterial: the test prototype we have implemented in our computer at FTL operates at the tactical, terminal area level; but the concept could equally well be implemented at the Central Flow Control level. It is far too early to decide whether these abstractions would be of any use in a future ATC environment or not; my purpose in presenting this work to you is only to show a different kind of "product" of Artificial Intelligence thinking in Air Traffic Control research.

The development of these abstractions began as an attempt to state, in knowledge representation terms, ⑮ the classical time-based Mefered Merge control problem, which can be simply stated as follows: merge two streams of incoming aircraft with random interarrival times to form a single output stream with uniform aircraft separation. This is usually performed by assuming an ideal "conveyor belt" of time slots, and by assigning aircraft from both incoming streams to a slot in the conveyor belt, and then maneuvering the aircraft – in the time dimension, hence the name "time-based" merge – to their assigned ⑯ slot. This maneuvering in time may, of course, require complex maneuvering in two-dimensional space.

The picture is a little more complicated when not two, but a number of incoming streams must merge into a single one: each route begins at one of the sources; the routes merge in pairs, until a single path arrives at the sink, thus creating a binary converging tree.

Previously developed algorithms assumed the existence of a centralized decision-making logic with direct and instantaneous access to all the information required to decide what maneuvers each aircraft should be required to perform to arrive at the ultimate sink at the desired spacing. While there is nothing theoretically wrong with this approach, and while it indeed works, from a mathematical standpoint, it creates an operational problem:

Flow control is only one of the tasks to be performed by the ATC system. Indeed, separation assurance is by far more important, in the short term, than orderly flow of traffic. For a number of technical, operational, and historical reasons, responsibility for separation assurance requires that ATC functions be divided into small sectors under the authority of a single human controller, as opposed to a central control authority. This "federated" approach, which is optimal for separation assurance and responsibility accounting, conflicts with the centralized approach of traditional flow control algorithms. In a federated approach, each control element – that is, each controller – interacts mainly with his immediate neighbors, rather than with a centralized arbitrator: handoffs are initiated, accepted, or rejected on a one-to-one basis, and not as a result of the decision-making of a central authority.

For this reasons, flow control procedures are difficult to implement and interface with in a federated ATC environment. It would be interesting to develop and test a flow control approach that operated as a number of independent elements which interact only among neighbors, in the same way tactical ATC elements do. This such approach, developed at MIT's Flight Transportation Laboratory, is called the "Metered Merge Control Element", or MMCE, concept. Again it is too early to decide if this approach has any merit or not, and I am presenting it here only to illustrate the kind of product that can be developed using the A. I. approach to computers. ⑰

Conceptually, the MMCE consists of the following elements: two "entry gates", a single "exit gate", and two "nominal transit times" from each of the entry gates to the exit gate. While it is useful to visualize the MMCE as a Y-shaped merging path, the geometry of the MMCE is irrelevant to the concept, except insomuch as the transit times are related to the size and shape of the paths.

Connected to the exit gate, each MMCE has a "downstream correspondent", which can be either another MMCE, or, in the case of the last MMCE of the tree, the aircraft sink. Connected to each entry gate is an "upstream correspondent", either another MMCE's or, in the case of the first MMCE's in the tree, the aircraft sources. Sources, MMCE's, and the sink comprise the entire Metered Merge flow control abstraction. This abstraction is independent of the scale of the problem: it could be the Terminal Area around an airport, with the sources being the feeder fixes, and the arrival runway; or it could be an enroute problem, with the sources being originating airports and the sink the destination airport's terminal area. In any case, the operation of the abstraction is as follows:

When an aircraft appears at a source, its existence is immediately made known to the MMCE immediately downstream of this source. In the absence of any flow control, that aircraft would reach the MMCE's exit gate at a time which is equal to the time at which the aircraft appeared, plus the nominal transit time through the MMCE's right or left branch, as appropriate. Therefore, that aircraft should appear at the entry gate of the current MMCE's downstream correspondent at that time. This information is passed on by the current MMCE to that downstream correspondent, who then performs the equivalent computation and passing of the information to *its* downstream correspondent. Finally, the ultimate downstream correspondent – the sink – is told that an aircraft would nominally reach it at a time equal to the current time plus the sum of the nominal times through all the appropriate branches of all the intervening MMCEs.

At this point, the sink has to perform its own decision-making, which may include previously received notifications of incoming aircraft. The result of this decision-making is a desired arrival time for that aircraft, which may or not be the nominal arrival time. This information must then be made known to all the MMCEs that the aircraft must traverse to get there. Since the sink only has communications with the last MMCE, this element receives the desired arrival time at the sink for that aircraft.

Now, the process used to propagate the nominal arrival time downstream is reversed, in that the MMCE's nominal transit times are *subtracted* from the desired arrival times before submission to the next upstream correspondent. Finally, the first MMCE (the one currently "responsible" for that aircraft) receives the time at which the aircraft should leave its exit gate so that, flying at the nominal speed through the remaining MMCEs, it would arrive at the sink at the time that the sink desires it.

Actually, this "upstream propagation" of information is not as symmetric with the downstream propagation as I described it. Indeed, when propagating the information upstream, each MMCE has to send it to its right or left upstream correspondent, as appropriate, a decision-making not required when propagating the information downstream.

In the FTL implementation, the MMCE concept is used to drive a Radar Controller's display; in this display, the MMCE's are made to correspond to actual converging ATC paths. After the upstream-downstream passes describe before, the MMCE currently "owning" and aircraft uses the desired exit time information to display a "slot" in the screen which travels downstream along the MMCE's "nominal path" at the right speed so as to arrive at each MMCE's exit gate at the desired time. In this way, each controller is given an indication as to how early or late the aircraft is with respect to the ultimate sink's wishes.

This display concept, or "conveyor belt" had been proposed before, although it has never been mechanized, even experimentally, beyond the final approach path. It is clear that this kind of display could be constructed without the need for MMCEs, downstream ripples, upstream ripples, and the like. But let us examine the advantages of this "federated" logic approach, as opposed to some centralized algorithm.

Assume the MMCEs correspond to actual control responsibility areas – either on a one-to-one basis, or several MMCEs to a controller position. Since all of the information flow occurs only between neighbors, there is the opportunity for an MMCE to alter, or modify the information for its own purposes while it passes through it. Assume, for example, that each MMCE keeps a record of all the scheduled desired arrival times of aircraft at its entry gates as it propagates that information upstream. It could then determine if the number of aircraft under its responsibility exceeds a certain value during a period of time. This could be used to "reject" the desired propagation times as it is "handed in" by the downstream correspondent during the upstream portion of the cycle.

Similarly, what to do when an upstream correspondent rejects a proposed desired arrival time – in an MMCE to MMCE transaction – could be based on *local* decision-making: if each MMCE also keeps track of what desired time slots it has propagated upstream, it may attempt to swap the rejected slot with a slot that was previously propagated through the other branch of the MMCE. Thus, a bargaining process very similar to to-day's handoff bargaining could be performed.

While the development of this abstraction does not imply its computer mechanization – it could be mechanized, for example, as a series of controller-to-controller interactions – we are able to simulate them, and therefore perform experiments with them, using software objects in Lisp in FTL's symbolic ATC simulator. A number of *instances* of sources, sinks, and MMCE's can be created, liked, and positioned interactively. Image objects corresponding to the MMCEs nominal paths and the previously described slots are created and manipulated as easily as numbers on a calculator or characters on a word processing system.

## 9. A DISTANT DREAM: THE CONTROLLER'S ASSISTANT

Finally, and as an example of a truly long-term possible application of Artificial Intelligence technology to Air Traffic Control, I would like to propose to you the idea of a "personalized controller's assistant". This device would consist of a knowledge base made up of four parts: a "general" part reflecting the generic kind of controller know-how that would be reflected, for example, in the Controller's Handbook, or in training material; a second part, at a higher priority level than the first, would include "position-dependent" knowledge, such as the route and airway structure pertinent to that facility, letters of agreement between facilities, and the like; the third part would include the daily weather, notam and similar information, while the last part be made up of the individual controller's preferences and personal techniques.

Exactly what functions such a system could perform is not very clear at this time; one possibility is to act as a "dummy" of the controller, that is, display for his benefit what control actions the clone would take. By periodically observing that "dummy controller" the human controller could detect his own blunders – specially missed control actions – early enough to take effective corrective action.

If such a feature is to be a real help, rather than an additional burden, it is likely that the display of such "dummy directives" would have to be at a rather high level of abstraction; for example, rather than the "clone" displaying the command "TW611 turn right heading 220", to which the human controller may think "Why is he doing that?", the display should read something like "I would like to send TW611 west to make him a little late on his turn to final, or else he's going to be to close to that heavy ahead of him".

The key characteristic of such a system would be its personalization capabilities: personalization with respect to the position being assisted, the current weather, navaid and traffic information, and, most important, the individual controller. The controller's individual knowledge base could, presumably, be part of his personal equipment for the duration of his career; if I may be allowed to dream for a few instants, I can imagine the days when the controller, upon taking over a position from the previous person, would insert his or her magnetically-coded i.d. card on the console, to indicate to the system that his personal knowledge base is to be used; this knowledge base would replace the previous controller's personal set of rules, and interact with the facility's rule set, as well as the "knowledge of the day" which was entered by the same shift supervisor that briefed the incoming controller on the day's situation. Thus, there is a one-to-one correspondence between one element of the knowledge base and the controller's basic training, knowledge of the local environment, personal controlling style, and knowledge of the current traffic, weather and facilities situation.

What the form of this knowledge would have will have to wait for the appropriate knowledge engineering to be performed; I can only venture to suggest that it will involve abstract concepts both intuitively obvious to the human and manipulable by the computer, similar to the "geographic location" and "intersection" objects of our symbolic Air Traffic Control simulator. The collection of abstractions – which would include both objects AND actions – would in effect create a rich, unambiguous and intuitively attractive language which could be useful not only for humans and machines to communicate, but even for human-to-human communications, much in the same way that the language Lisp is to-day used not only to program, but also to describe logical process in scientific publications.

The same uncertainty about how knowledge would be represented in such a system also applies to what kind of "inference engine" or rule-processing logic it should have; to begin with, several simultaneous goals may be required, and these goals may be more complex than the simple diagnosis-seeking of MYCIN or the runway configuration change program of Tower Chief. Certainly, to-day's Expert System technology is not sufficient to achieve this functionality, and you should mistrust anybody who claims so. But I strongly feel that we should look for desired effects, influenced by what we expect will be the capabilities of technology in the future, and *then* look for the specific technology required to achieve them, rather that try to find applications for an existing technology that appears to be "a solution looking for a problem".

## 10. A FINAL CAVEAT

As ambiguous as all these promises are, they appear to hold a lot of promises for performance that we know cannot be achieved by to-days computational techniques. It is also fair, however, to point out some potential problems, principally that of software verification and validation. A significant part of the cost of to-day's software is associated with achieving a satisfactory degree of confidence that the behavior of the software in a system as critical as the Air Traffic Control system will be "correct". The cost of this validation increases, of course as the complexity of the desired behavior increases; the problem with the "personalized algorithm" I just described is not only that its behavior is radically more complex than that of any software ever used in Air Traffic Control automation, but that its behavior cannot, by definition, be completely known and specified a-priori!

This problem is not unique to the "controller clone" idea; indeed, imprecise a-priori knowledge of the behavior of the system seems to be a fundamental feature of most AI-oriented devices. What is the solution, then? Abandon this class of software as untestable? Abandon the notion that we can validate the software to be used in Air Traffic Control? Both extremes seem unjustified to me. I believe that a new concept of "software reliability" must be developed, a concept more sophisticated than just the idea that "it meets the prescribed specifications". For example, the notion of a "software defect" could be organized in various categories: category one would be a software defect that simply and catastrophically causes the entire system to stop functioning. Probably we can devise methods for testing against that type of bug, no matter how complex the software and the expert system rules become.

A second category of bug would involve a less than perfect solution to a problem (such as *not* finding a solution to a specific problem). In this case, it is clear to the user that the system is not functioning properly in that particular instance, but in all likelihood it will function properly on the next problem. This I would categorise more as a performance limitation of the technology than a real "bug", and the difficulty here is that we cannot predict – therefore specify – what the performance of an A. I.-based product will or should be; we will have to learn to live with this type of software deficiencies. A final, and perhaps the most devastating type of "bug" would be one which involves a definite malfunction whose effects, however, are not immediately apparent to the user. Such a defect, for instance, would involve making decisions about an aircraft on final approach using data pertaining to another aircraft on final approach; since the aircraft are in similar situations, the control actions suggested may look reasonable for the aircraft in question – even though they were based on information about the wrong aircraft.

How would one protect itself from such defects? Perhaps a way out would be to implement *software redundancy* in the same way as today we implement hardware redundancy to protect against hardware malfunctions. The notion of redundant software is, however, very different from that of hardware redundancy: while two identical ILS receivers do offer a significant amount of protection against receiver failure, two copies of the same program offers NO protection against a programming bug; indeed, programs (or, in the case of A. I. products, the rules or other language-data that determines the behavior of the program) must be independently developed, implemented, *and tested*, to offer any degree of protection.

We are at the very infancy of software redundancy; indeed, with to-day's programming technology, exhaustive validation and verification is cheaper than redundant software development. With the next generation software technology and systems complexity, is it possible that redundant software development may be the cheapest way – or maybe the only way – of gaining confidence in critical software.

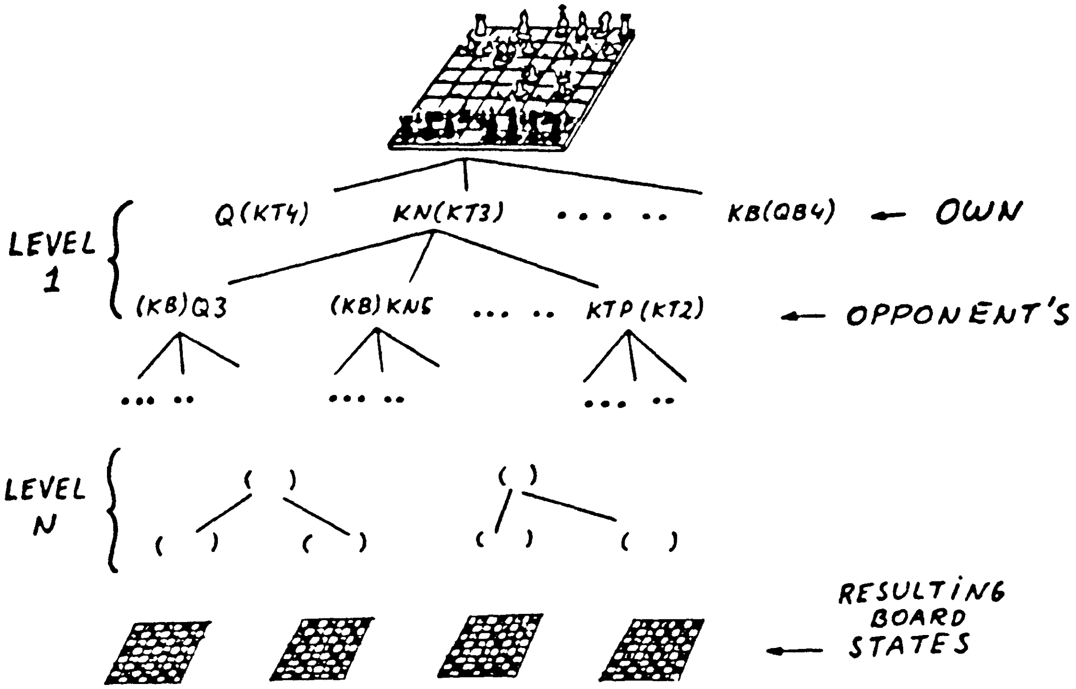
And this is all for today; before I conclude, I would like to point out that I have mentioned only ideas developed at M.I.T.'s Flight Transportation Laboratory. Other organizations are actively exploring other ATC applications of A. I. technology; I would like to mention in particular the work on Tactical conflict resolution at MITRE, and Weather Radar feature recognition and extraction at Lincoln Laboratory.

To summarize, I believe that Artificial Intelligence is a source of extremely powerful tools and ideas, and in particular, opens up a new viewpoint on the use of computers for any kind of application; one should not expect miracles from this technology in the near future, except perhaps in the areas of software productivity and simulation technology. I would like to compare the state of A. I. today, with that of the transistor in the late 1950's. At that time, there was little a transistor could do that could not be done with vacuum tubes. Admittedly, the transistor was a little smaller and used a little less power than a vacuum tube, but in many respects, such as frequency response, it was, in fact, inferior. Yet to-day, it would be a little hard for me to walk around with a wrist watch that computes inverse trigonometric functions if it were built with vacuum tubes, even if I had a long enough extension cord! So, sometimes between 1960 and 1985, the mere quantitative advantage that the transistor had over the vacuum tube was transformed into an insuperable qualitative advantage. Perhaps we will wake up some day in the year 2000 and realize that sometime between 1985 and then, the mere quantitative differences between Artificial Intelligence and conventional use of computers was also transformed.

But we should be very careful not to *demand* that this transition occur within a designated period of time. If, in 1957, Doctor Schockley would have been required, in order to continue work with his invention, to show a use of the transistor that could not be performed with a vacuum tube, he just might have given up and gone home. Let us be careful not to require a similar performance from Artificial Intelligence, or we may loose one of the most significant intellectual developments of mankind since the printing press. Thank you very much.

## 11. ACKNOWLEDGMENTS

Research described in this lecture has been sponsored by the Federal Aviation Administration and the Transportation Systems Center of the U. S. Department of Transportation. The author wishes to recognise the important contributions of the following individuals: Prof. Robert Simpson, Dr. John Pararas, Mr. Lyman Haselton and Mr. Jim Butler from the M.I.T. Flight Transportation Laboratory; Mr. John Fabry from the F.A.A. Technical Center, Atlantic City; Mr. Richard Wright from the Transportation Systems Center, Cambridge; and Messrs. Paul Newman and Steve Alvania from the Federal Aviation Administration Headquarters, Washington.



Viewgraph number ①

*FLIGHT TRANSPORTATION LABORATORY*

MASSACHUSETTS
INSTITUTE OF
TECHNOLOGY

## A TYPICAL MACSYMA SESSION

```
(C1) x = 3 * y^2 - 2 * y + 17;
                                        2
(D1)                             X = 3 Y  - 2 Y + 17


(C2) solve(d1,y);

                     SQRT(3 X - 50) - 1      SQRT(3 X - 50) + 1
(D2)           [Y = - ------------------, Y = ------------------]
                             3                        3


(C3) integrate(part(c1,2),y);
                                   3   2
(D3)                              Y  - Y  + 17 Y
```

Viewgraph number ②

## A TYPICAL MACSYMA SESSION (CONT.)

```
(C4) sqrt((x+1)/(x-1));
                                        X + 1
(D4)                               SQRT(-----)
                                        X - 1

(C5) integrate(d4,x);
                      X + 1                   X + 1                X + 1
             LOG(SQRT(-----) + 1)    LOG(SQRT(-----) - 1)     SQRT(-----)
                      X - 1                   X - 1                X - 1
(D5)  - 4 (- -------------------- + -------------------- - --------------)
                       4                        4           2 (X + 1)
                                                             --------- - 2
                                                               X - 1


(C6) ratsimp(d5);

                X + 1                  X + 1                      X + 1
(D6)   LOG(SQRT(-----) + 1) - LOG(SQRT(-----) - 1) + (X - 1) SQRT(-----)
                X - 1                  X - 1                      X - 1
```

Viewgraph number ③

## A TYPICAL MYCIN SESSION

```
---------- PATIENT-1 ----------

1) Patient's name: (first-last)
*** Fred Smith

2) Sex
*** Male

3) Age:
*** 55

4) Have you been able to obtain positive cultures from a site
at which Fred Smith has an infection?
*** Yes

---------- INFECTION-1 ----------

5) What is the infection?
** Primary-bacteremia
```

Viewgraph number ④

## A TYPICAL MYCIN SESSION (CONT.)

```
6) Please give the date and approximate time when signs or
symptoms of the primary-bacteremia (infection-1) first appeared
(mo/da/yr)
*** May 6 1980

The most recent positive culture associated with the
primary-bacteremia (infection-1) will be referred to as:

---------- CULTURE-1 ----------

7) From what site was the specimen for culture-1 taken?
*** Blood

8) Please give the date and time when this blood culture
(culture-1) was obtained. (mo/da/yr)
*** May 9 1980

The first significant organism from this blood culture
(culture-1) will be referred to as:
```

Viewgraph number ⑤

---

## A TYPICAL MYCIN SESSION (CONT.)

```
---------- ORGANISM-1 ----------

9) Enter the identity of organism-1:
*** unknown

10) Is organism-1 a rod or coccus:
*** rod

11) The gram stain of organism-1:
*** gramneg

12) Have there been positive cultures from sites which are NOT
associated with infections about which you are seeking advice?
*** no

13) Did organism-1 grow aerobically?
*** yes (0.8)

14) Did organism-1 grow anaerobically
*** yes
```

Viewgraph number ⑥

## A TYPICAL MYCIN SESSION (CONT.)

```
15) What is the suspected portal of entry of organism-1 into
this sterile site?
*** GI (0.6)
                 . . . . . . . . . . . .

My therapy recommendation will be based on the following
probable infection(s) and potential causative organism(s):

INFECTION-1 is PRIMARY-BACTEREMIA
<Item 1> The identity of organism-1 may be PSEUDOMONAS-AERUGINOSA
<Item 2> The identity of organism-1 may be KLEBSIELLA-PNEUMONIAE
<Item 3> The identity of organism-1 may be E.COLI
<Item 4> The identity of organism-1 may be BACTEROIDES-FRAGILIS
<Item 5> The identity of organism-1 may be ENTEROBACTER
<Item 6> The identity of organism-1 may be PROTEUS-NON-MIRABILIS

46) On a scale of 0 to 4, where higher numbers indicate
increasing severity, how would you rate Fred Smith's degree
of sickness?
*** 3
```

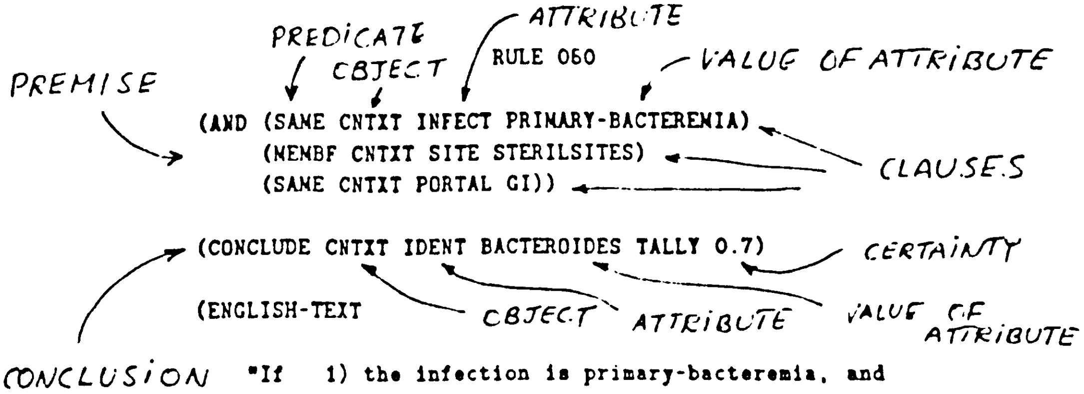
Viewgraph number ⑦

## A TYPICAL MYCIN SESSION (CONT.)

```
47) Does Fred Smith have a clinically significant allergic
reaction to any antimicrobial agent?
*** no

48) Fred Smith's weight in kilograms (or <number> pounds):
*** 70

[Rec 1] My preferred therapy recommendation is as follows:

In order to cover for Items <1 2 3 5 6>:
     Give: GENTAMICIN
     Dose: 119 mg (1.7 mg/kg) q8h IV [or IM] for 10 days
               Comments: Modify dose in renal failure

In order to cover for Item <4>
     Give: CLINDAMYCIN
     Dose: 595 mg (8.5 mg/kg) q6h IV [or IM] for 14 days
     Comments: If diarrhea or other GI symptoms develop,
               patient should be evaluated for possible
               pseudomembranous colitis.
```

Viewgraph number ⑧

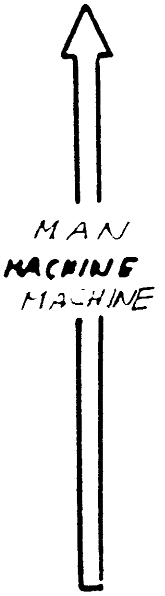
## A TYPICAL MYCIN RULE



```
RULE 060

(AND (SAME CNTXT INFECT PRIMARY-BACTEREMIA)
     (MEMBF CNTXT SITE STERILSITES)
     (SAME CNTXT PORTAL GI))

(CONCLUDE CNTXT IDENT BACTEROIDES TALLY 0.7)

(ENGLISH-TEXT
```

"If 1) the infection is primary-bacteremia, and
2) the site of the culture is one of the sterile sites, and
3) the suspected portal of entry of the organism is the gastrointestinal tract,

Then there is sufficient evidence (0.7) that the identity of the organism is bacteroides.")



PROBLEM CONCEPT
("LOGIC PROGRAMMING"?)

"Acceleration is the derivative of velocity"
"Keep all aircraft velocities constant"

SYMBOLIC PROGRAMMING,
ACTIVE OBJECTS

```
(DOLIST (A/C AIRCRAFT-LIST)
   (SEND A/C :SET-ACCELERATION 0))
```

- - - - - - - - - - MAN-MACHINE INTERFACE - - - - - - - - - -

HIGH-ORDER LANGUAGES,
ARRAYS, VECTORS

```
FOR I=1 TO NO_OF_AC DO
  CALL SUPROD (ACCVEC, VVECT, RESULT)
    FOR I=1 TO 3 DO; A(I)= A(I)-RES...
       ....
```

ASSEMBLY CODE,
MNEMONIC LABELS

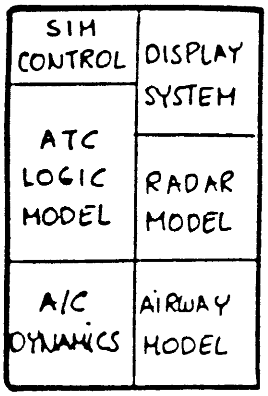
```
LDY #01
LDA VEL,Y
CMP #$00
BNE LABEL3
```

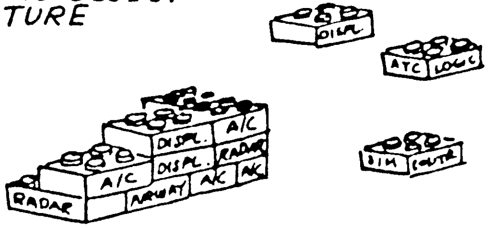
BIT-LEVEL CODE,
DATA

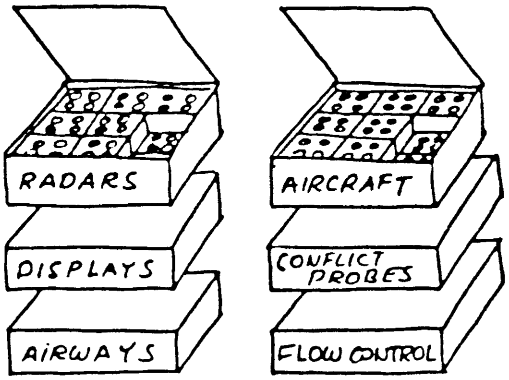
```
40605D7013FFFD....
```

TRADITIONAL (MODULAR) SIMULATION STRUCTURE

SIMBOLIC-OBJECT STRUCTURE







Viewgraph number ⑪

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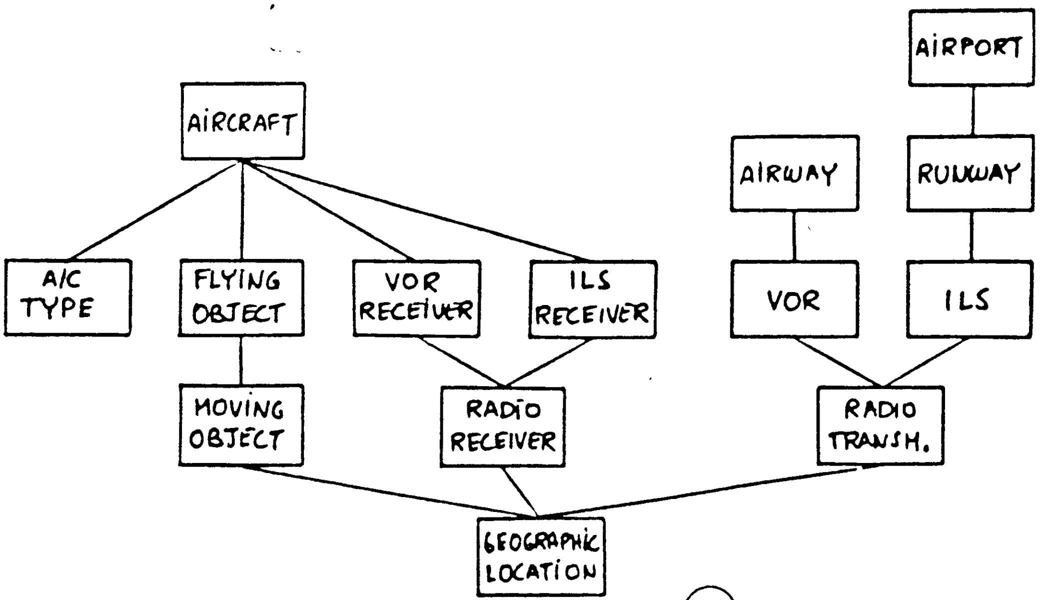
TYPICAL SYMBOLIC-OBJECT SIMULATION OBJECT STRUCTURE.



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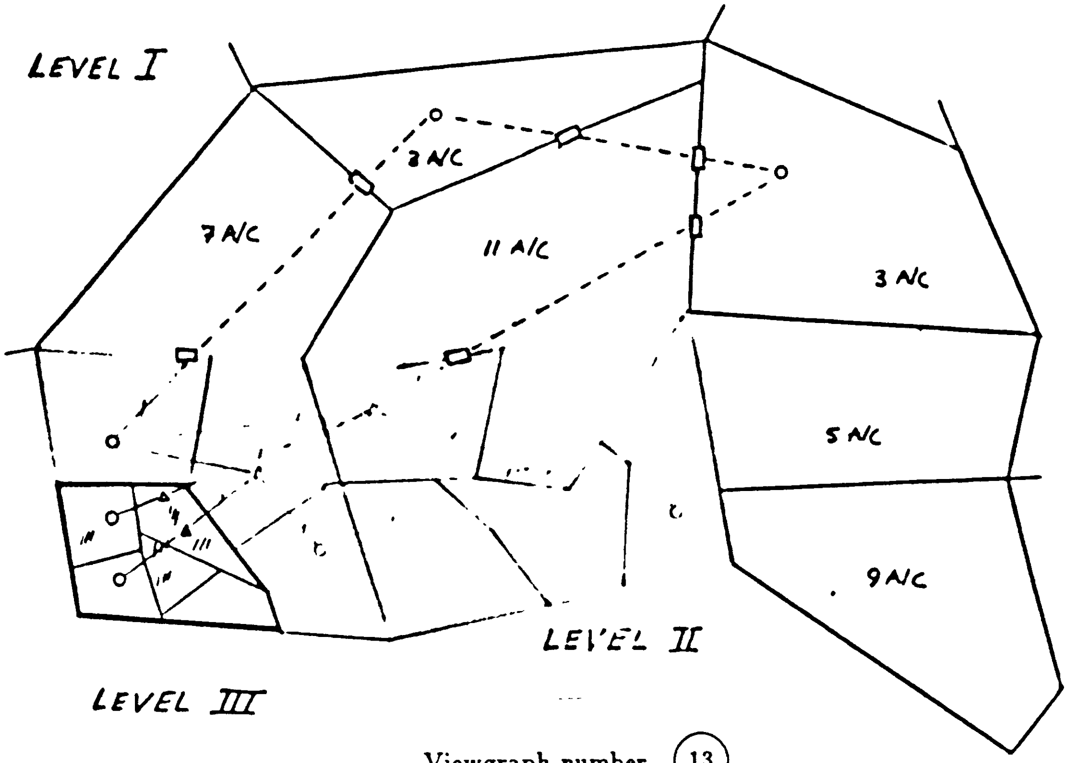

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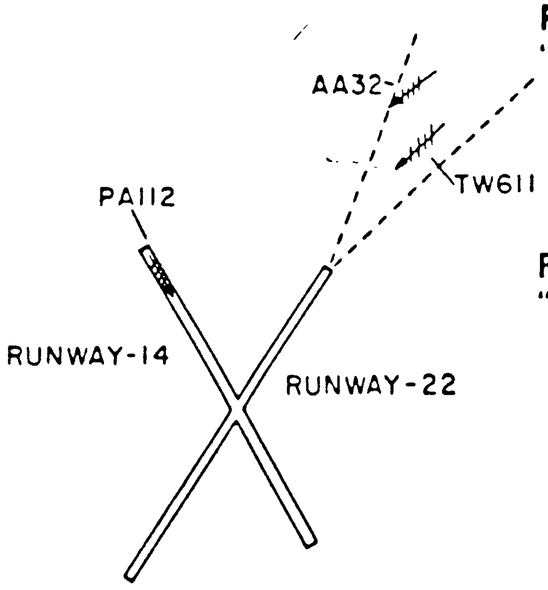
TYPICAL TOPOLOGY OF CONTROLLER'S PROCESS



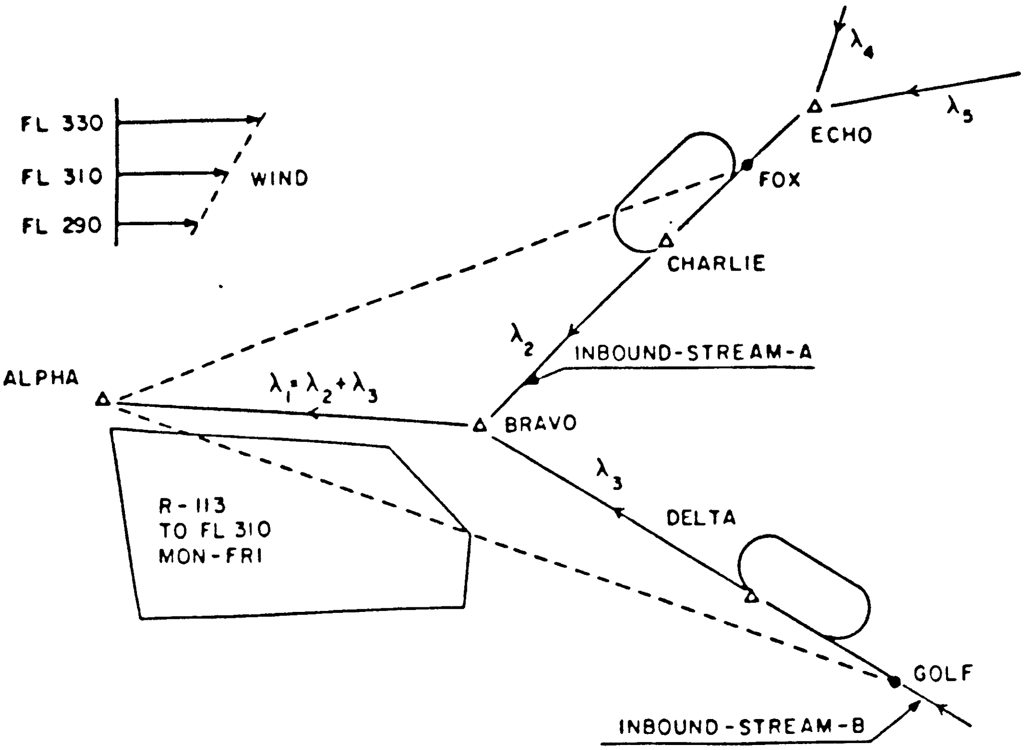
**RULE-1** (AIRCRAFT1, RUNWAY1):
"IF AIRCRAFT1 IS-TRYING-TO-LAND-AT RUNWAY1
IS TRUE AND
AIRCRAFT1 IS-CLEARED-FOR-APPROACH-TO
RUNWAY1 IS FALSE THEN
ALERT USER"

**RULE-2** (AIRCRAFT1, RUNWAY1):
"IF AIRCRAFT1 IS-CLOSE-TO RUNWAY1 AND
ABS (AIRCRAFT1 COURSE - RUNWAY1 HEADING)
LESS THAN $\epsilon$ AND
ABS ((RELATIVE-BEARING (AIRCRAFT1 POSITION)
(RUNWAY1 TDZ)) -
RUNWAY1 HEADING) LESS THAN $\epsilon$ AND
AIRCRAFT1 ALTITUDE-AGL LESS THAN 1500 THEN
ASSERT AIRCRAFT1 IS-TRYING-TO-LAND-AT
RUNAWAY1 TRUE"

**RULE-3** (AIRCRAFT1): ASSERT AIRCRAFT1 COURSE $_{\text{TAN}}\text{-}1 \, \frac{({}^{X}1 + {}^{X}2 + {}^{X}3)}{({}^{Y}1 + {}^{Y}2 + {}^{Y}3)}$

Viewgraph number ⑭

## STREAM MERGE PROBLEM



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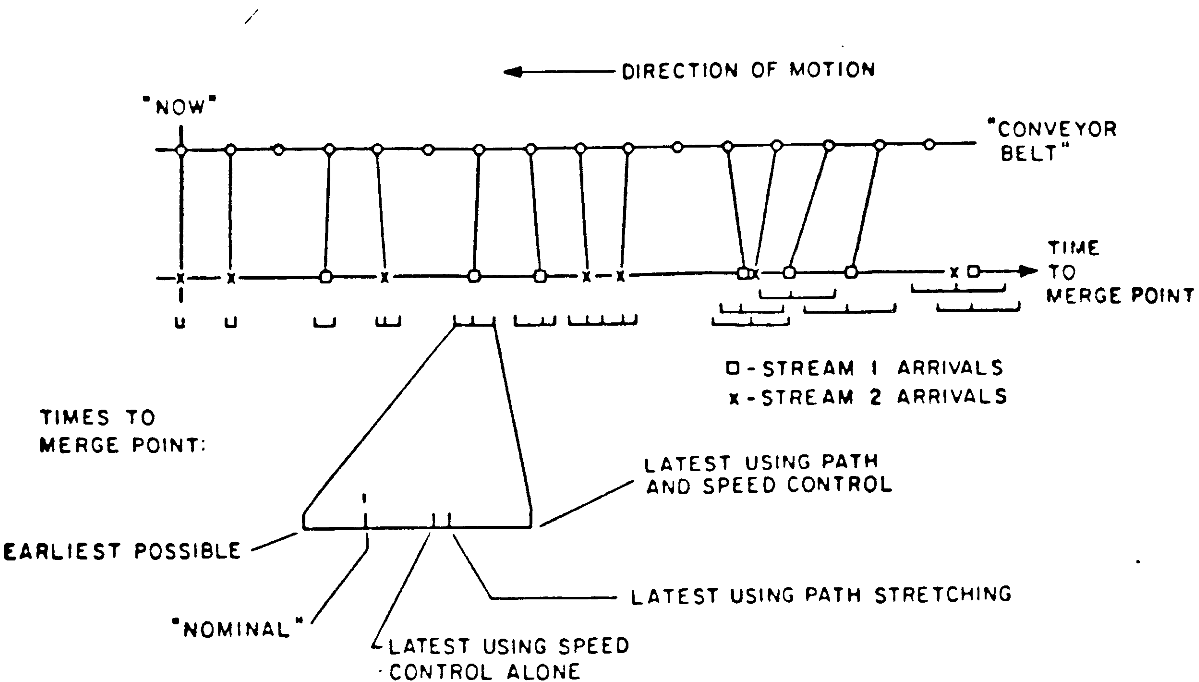
## TIME-BASED METERED MERGE-BASIC MODEL



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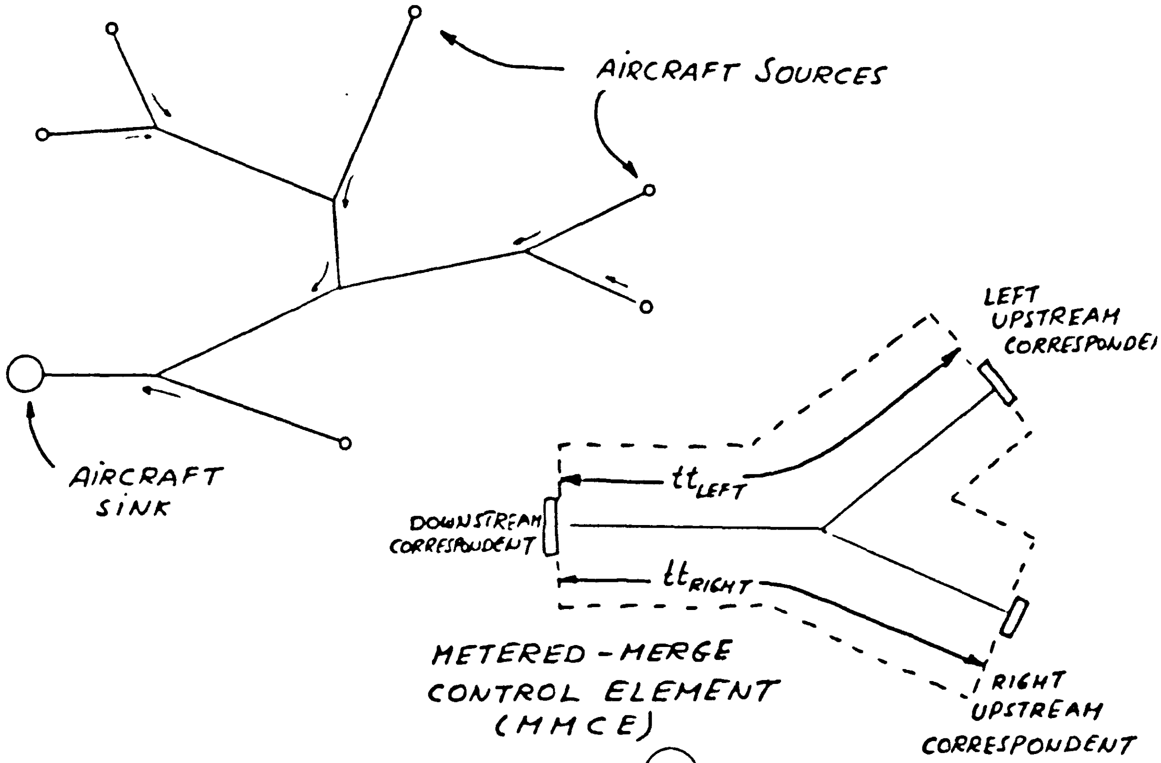

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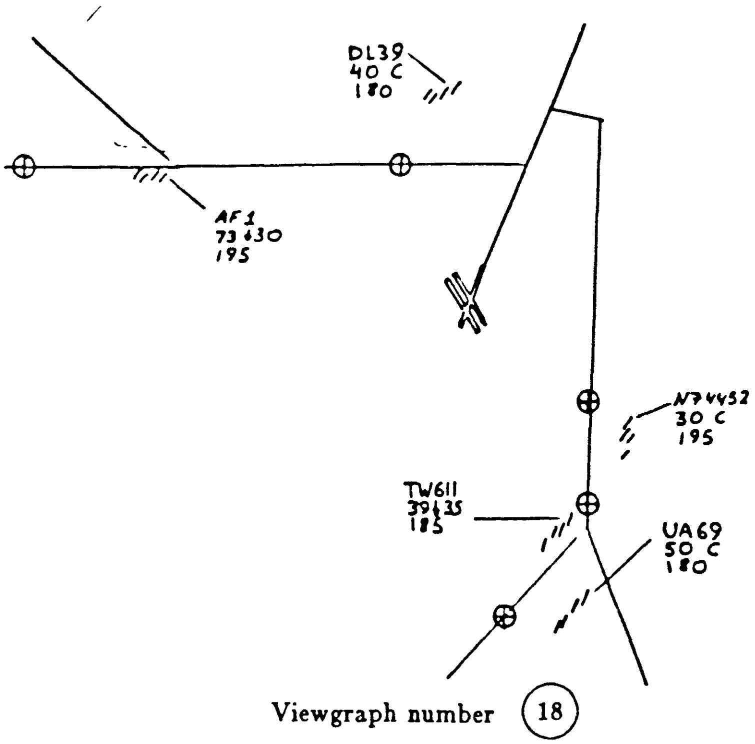

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