Computer graphics for transportation problems*

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INTRODUCTION

The central problem in designing transportation systems and networks is determining the optimal control techniques for given transportation facilities. For example, it is essential to find the best strategy for handling the traffic in a given airspace, in a given highway system, or in a network of city streets. The other side of the problem is to determine for given or predicted traffic conditions, the optimal transportation facilities. Urban planners must solve these problems when designing new developments; similarly it is important to determine how many airways and airports will be required to handle the air traffic in the 80's. From the answers to such questions one can decide how to allocate funds, for example, to improve the radar systems to allow smaller separation or to put more navigation aids in order to increase the number of airways.

It is not just a mere coincidence that in many languages the word “see” and “understand” are synonyms. In many cases to see is to understand, and this is what computer graphics is all about.

Computer graphics is used mainly as an interface between the man and the machine. Problems which inherently require display of output or have graphically oriented input are the clearest beneficiaries of computer graphics. Graphical output gives the ability to display arbitrary shapes quickly. Graphical input provides the ability to define shapes and the ability to identify things naturally by pointing to them. Transportation systems are often best represented graphically. For these reasons we have found that the application of computer graphics techniques to the solution of transportation problems is most fruitful.

In this paper we discuss the philosophy behind our approach, and illustrate it with examples taken from specific programs. A ten minute film will be shown to demonstrate the application of interactive computer graphics for urban traffic problems.

COMPUTER APPROACHES FOR TRANSPORTATION SYSTEMS

It is often the case that practical problems deal with system behavior, rather than behavior of a single particle or a single element. Describing and dealing with systems is manyfold more complex than working with a single element. Often one can describe very precisely the exact mathematics which govern the behavior of a single element. However, it is very seldom that one can find equations which describe a system completely, and still be consistent with the behavior of each of its elements.

Simulation of urban traffic, or air traffic, are examples of this difficulty. One can describe very precisely the motion of a single car or of a single airplane. If the motion of the car is unrestricted, then its behavior is simple to explain. When more than one element is introduced into the system, the interaction between them adds a new dimension to the problem. The complexity of the interactions might grow as the square of the number of objects in the interaction. In general, one can solve situations where few vehicles are involved. However, any practical problem involves too many objects for a human being to solve without a computer.

In many transportation problems, there is a system of many particles moving concurrently in the same space, obeying some interaction restrictions. These restrictions are usually in the form of separation criteria (for cars, airplanes, ships, etc.), staying in some corridors (like highways, airways, etc.) sharing some navigation facilities and so on. Such system problems lend themselves very well to computer use. In order to solve these transportation systems on a computer, one can

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use simulation techniques, rather than integrating equations into system-behavior. A computer can perform the tedious job of simulation particle by particle and make local decisions about each of the particles. In some systems these decisions are based only on local information, as observed by each particle. In other systems these decisions may depend on global information about the state of the system.

If the behavior of each individual particle is non-deterministic and some distribution and probabilities are involved in the description of each particle, then the behavior of the entire system is non-deterministic; in order to simulate it properly one has to simulate the distributions. These non-deterministic simulations have to be repeated many times in order to average the behavior and the distribution to get meaningful results. Clearly, it is appropriate to use a computer for such simulations.

Computer graphics lends itself very well to this kind of simulation. After every updating cycle, one can display the state of the system. For example, if one simulates the air traffic in a given space based on some known rules, one would like to observe the dynamics of the system changes. The visual display of this information, at a rate meaningful for the viewer, might introduce new understanding of the behavior of the system. In the case of traffic simulation, whether it is urban traffic or air traffic, one can learn a great deal by viewing the intermediate steps through which the system is going.

For example, one might observe that due to some latency in traffic lights, some cars happen to jam an intersection, which in turn might cause a total breakdown of the traffic flow. If the conditions of cause and effect are not known in advance, global measures are not enough to explain this kind of behavior. The only way to understand the system is by viewing it, and recognizing its behavior patterns. These patterns, which are not known before they are observed, rely very highly on the intelligence of the human being and his ability to recognize patterns. If the behavior patterns are already known, one might assign the computer to look for them, measure them, and report them. This can be done off-line (batch processing, for example) and interactive graphics is not needed for it. However, in many cases the internal behavior patterns are not known and one has no idea what to look for, and cannot assign the computer to search for and measure them. The dynamic graphic simulation allows one to see and recognize behavior patterns which he never expected to find, and watch them develop. This recognition leads to an improved understanding of the system.

INTERACTIVE COMPUTER GRAPHICS FOR SIMULATION PROBLEMS

Under many circumstances, the best use of a computer simulation is an interactive one. There may be so many variables that the only way to understand their interdependence is to study the problem in real-time simulation, seeing how it is affected by various changes. There may be such uncertainty in the model itself that the parameters should be altered as the simulation proceeds. Using this approach, one can quickly gain a good understanding of the model's strengths and weaknesses, its suitability to certain situations, and its sensitivity to incremental changes of many kinds. Such an intuitive appraisal of a model is frequently more valuable than extensive numerical evaluations. The conditions of a smoothly flowing dialogue are decidedly more conducive to thought than the use of a computer merely as a calculating machine.

We felt that an interactive system would be desirable in view of the nature of problems in traffic flow. They are infinite in variety, yet they can be formulated intuitively. We have daily experience with many of these problems, and we know how traffic behaves under many conditions. Since these perceptions are often difficult to include in a precise model, it is to our advantage to exercise a model in an interactive way, and supply it with our reactions as the simulation takes place. We are then employing the computer where it is most useful in the problem-solving process.

Interaction with a computer simulation becomes much easier for a man, as well as a more valuable technique, when results are supplied quickly and clearly in picture form. Pictures carry immediate meaning; details and patterns can be recognized easily, and factors of cause and effect are evident. When he changes the conditions of the problem, he gets meaningful results right away and is therefore in an excellent position for further interaction. He may continuously change the parameters and see the sensitivity of the system to these incremental differences. This kind of continuous dialogue, uninterrupted by technical details, is a powerful and valuable method of investigation. A man is thus able, with computer assistance for computation and communication, to solve many problems beyond the scope of a man alone or an off-line computer program.

Just as graphical output is the natural form for the machine-to-man communication, graphical input is the natural form for the man-to-machine communication. Many transportation problems require a specification of a map and associated parameters. This can be done initially in a digital form; however, it is much more
convenient and natural to input this information graphically, by using stylus-like devices. Furthermore, during run-time the need often arises to identify particular objects, which may be in motion. It is most natural and efficient for a man to do so simply by pointing at them with his stylus.

It is most important to provide the transportation-engineer with natural means for communicating with the computer. He should be able to concentrate solely on solving the specific transportation problem, rather than concerning himself with the details of computer operations.

AN EXAMPLE OF URBAN TRAFFIC

Mr. John M. McQuillan, then a senior at Harvard College, constructed a program to simulate urban traffic, based on the principles of interactive graphics discussed above. The user of the program begins by specifying the street map to be considered. This is accomplished by means of a stylus and a tablet. The user specifies the position of the streets, their direction and number of lanes, and the program draws in the streets and the intersections for him. He defines whether an intersection is controlled by a traffic signal, a stop sign, a yield sign, and so on. These symbols are drawn for him automatically. This definition process is interactive, allowing the user to edit the map at any time. He may reposition portions of the map, delete and add sections as he wishes. After the street map is drawn, the user can specify automatic settings for the traffic signals. He does this by drawing a bar graph of the times during a fixed-length cycle when the light is to be green and when it is to be red. He also has the facility of assigning the same setting to other signals, or the same setting with a fixed delay time. He may also specify that certain signals are to be given the same settings and then perform the above operations on groups of signals rather than single ones. In this way, it is relatively easy to construct a strategy of traffic signal settings for a complex network of intersections.

Next, the user directs the program to enter the simulation phase. In this stage, one CRT shows the street map, with cars travelling through it, obeying the traffic laws and signal settings. Each car moves through the streets, turns, pauses, switches lanes, etc., according to information based on the surroundings. This is illustrated in Figure 1. Meanwhile, another CRT shows the automatic signal settings in a form of bar graphs. A cursor moves along these bar graphs, indicating the signal changes as they happen. This is illustrated in Figure 2. At the same time, a third CRT shows a control panel with bar graphs which govern several parameters. These parameters include traffic density in each direction and some other characteristics. As the simulation proceeds the user may change any parameter merely by pointing to the bar graph with his stylus. This control panel is illustrated in Figure 3. In addition, this third CRT displays instantaneous and cumulative statistics, such as number of cars inside the map, average speed and so on.

The program is designed so that it is natural to use interactively. After specifying one map, the user can try different signal settings under different traffic conditions to find appropriate means of control. He sees the effects of these changes in real time, as traffic flows through the network. He may return to draw in a new map and alter his strategies further, all in an interactive manner. We have found this approach to be a very valuable one in formulating and solving problems in urban traffic.

AN EXAMPLE OF AIR TRAFFIC

The air traffic control problem is a unique problem in the sense that it involves a very complex system of many airplanes sharing the same air space concurrently. In order to describe the system of the air traffic, one needs a dynamic tool which enables him to describe in
Figure 2—Signal settings for traffic simulation—This is a display of the time settings of the traffic signals (letters on the graphs identify individual signals). For each traffic light, a bar graph represents those times that the light is green and the absence of a bar indicates when it is red, during a 100-second cycle. The vertical bar is a cursor which moves across the graphs in real time the current positions of many airplanes which move in different directions at the same time. There is no way but graphically to describe the state of the system at any time. In real life the way the air traffic system is described is by graphical means, the radar which is used by the controllers. The control information which is issued is in the form of instructions to the airplanes telling them positioning and timing information, issuing “vectors,” instructions for turning, and so on. Because of the nature of the problem, it is desirable to have facilities that enable one to communicate with the system graphically for input control information and to receive the state of the system at any point. For example, a controller should be able to define a route for an airplane merely by drawing the route on the face of a scope rather than verbally describing it. Collision hazards should be represented to the controller by showing him two airplanes whose routes tend to merge, and perhaps flashing some warning lights to attract his attention to this fact. The interaction between the controllers and the real airplanes should benefit from the use of the graphics as well. The controller should be able to point to an airplane rather than calling it verbally. This assumes, of course, that the system behind the graphics is aware of which airplane is where, and can automatically issue some communication to this airplane upon graphical request of the operator. In order to demonstrate these ideas and to provide a training environment, a computer program was developed in our laboratory.

In the first phase of the program, which was written by Mr. Geoffrey A. Modest, then a junior at Harvard College, one can define the map of the area in which he wants to operate, and assign it any arbitrary shape. One can define the shape and the position of the airports to be included in this area. One can define the “Victor” and the “Jet” airways intersecting this area, and can define standard holding patterns. Navigation aids can be introduced into the map in the shape of triangles and squares. This definition state is, of course, interactive. One can change his mind during the definition stage or later by editing the map, changing it, deleting obsolete objects, and adding new features to it.

After the definition phase, the operation phase begins. This section was written by Mr. W. B. Barker, a graduate student at Harvard University. This operation phase requires two people to operate it. One simulates the air traffic controller and the other one simulates concurrently all the pilots of all the airplanes in the area. The “pilot” can issue routing instructions
to each airplane in graphical form. The routing instruction may have the form of “climb and maintain flight level 200,” and “follow victor 20, turn to victor 16 at station x,” etc. The “controller” can see on his scope the position of each airplane and can interrogate these airplanes graphically, requiring information about altitude, speed, identification, and so on. Ideally, the controller should be able to express instructions to the airplanes graphically. However, in order to simulate closely today’s systems, the program does not automatically carry the graphical instructions of the “controller” to the airplanes, but the “controller” has to issue them verbally, as if he were talking on radio to the pilot. The “pilot” then can apply these instructions to the airplanes, exactly according to the “controller’s” instructions, or he may deviate from them. This way the “pilot” can simulate misunderstandings between the air traffic control and the pilot in the air. The only way that the “controller” can find about these misunderstandings is by noticing, on his “radar,” that some airplanes do not follow the instructions that he had issued before. All communication with the airplanes either by the “pilot” or the “controller” is very natural. In order to specify an airplane all they have to do is to “touch” the airplane on the scope with a stylus. All control information is requested graphically, and the flight paths of the aircraft on the radar screen provide the necessary feedback.

FUTURE APPLICATIONS OF COMPUTER GRAPHICS IN TRANSPORTATION

We hope that the programs we have developed will be prototypes for future practical systems. Many different aspects of transportation problems could benefit from the introduction of computer graphics tools. Initially, we have been concerned with the design problems that city planners and others face, and the resource allocation and management questions that arise in the creation or expansion of transportation facilities. It is a tremendous saving in time and money for the design engineer to be able to experiment with alternate approaches by computer simulation rather than by actual experiment. Just as major costs can be avoided by graphics simulation in the planning of a new airport or highway, minor modifications to existing facilities can be accomplished with far greater ease. Here too, the advantages of different approaches can be evaluated carefully ahead of time. The manager can get a clear picture of the effectiveness of various proposals from the simulation, and weigh this against other factors of cost and feasibility. Indeed, he need not wait until he is forced to expand or alter the available facilities before he turns to a computer graphics simulation. He could keep an up-to-date model of his facilities for computer use, and periodically test this model under varying conditions. In this way, problem areas may be diagnosed before they become dangerous or expensive, or both. Computer simulation is obviously superior to actual measurements and experiments in examining future loads on a transportation system. The air traffic control program can simulate anything from private planes to SSTs not yet developed. Of course, the manager could also concentrate on getting the best performance out of the existing facilities. Using the computer graphics method, he can satisfy himself that a certain system of routing and control is optimal before he tries it out. It should be noted that the practical experiences of the people using the graphics system can be continuously applied in a feedback loop to improve the quality of the computer simulation.

Another aspect of a highly interactive graphics system is its suitability for educational use. Traffic engineers can receive a great depth of training from a realistic simulator. Air traffic controllers can learn about many emergency situations and alternate strategies to employ. Watching a dynamic model of a transportation system is an excellent way to learn about its behavior and how to control it effectively. Not only is it a good introduction to a particular situation, but it provides a means of studying subtle problems that may otherwise be impossible to observe. This power comes from the man’s ability to control the scale and focus and speed of the simulation interactively, as it proceeds, ignoring routine patterns, and closely examining critical decision areas.

For educational use, design analysis, and practical decision-making, the interactive graphical simulation promises to be a useful tool in the field of transportation.