Brief Papers

Distributed System-Level Control of Vehicles in a High-Performance Material Transfer System

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Abstract—**In this paper, a fully-distributed system-level control architecture is described for dispatching, routing, and collision avoidance of multiple passive vehicles moving in a guideway network formed by a multitude of propulsion units. Propulsion units cooperate using a communication network with a topology identical to that of the guideway network, eliminating the need for explicit knowledge of global topography and enabling rapid real-time response to service requests using a parallel, shortest-route algorithm. The concepts developed are applied to a high-performance system in which vehicles respond to spontaneous requests to transfer material from point to point in manufacturing facilities in seconds rather than the minutes required in conventional AGV and conveyor systems. In this application, the vehicle and propulsion-unit lengths are on the same order of magnitude, the propulsion-unit-length/maximum-vehicle-velocity time characteristic is small, and the ratio of the number of propulsion units to the number of vehicles is large.**

I. INTRODUCTION

THERE has been a trend towards distributed control in automated transport systems since the early stages of their evolution when it was recognized that centralized approaches would be unable to meet the computing and communication demands of physical control of multiple vehicles [1]. Consequently, centralized physical controllers rapidly evolved into distributed [2] and decentralized controllers [3] that have performance comparable to optimal centralized controllers but require significantly lower computing and communication capabilities. The bulk of research to date has been focused on control of individual vehicles [4], [5] rather than the "distribution of intelligence that places maximum emphasis on self-sufficient vehicles" [6].

In one class of automated transport systems that has been studied at the University of Wisconsin-Madison, multiple passive vehicles are driven through a geographically distributed, stationary actuator consisting of a multitude of propulsion units [7]. Specifically, an automated material transfer system has been studied for application in manufacturing where cutting tool deliveries to and from machine tools are to be made spontaneously and nearly instantaneously relative to workpiece machining times. Each propulsion unit in the automated material transfer system studied is approximately 1 m in length and consists of a stationary-primary linear induction motor (LIM) capable of full physical state control (position, velocity, acceleration) of a single moving secondary approximately 0.25 m in length with a closed-loop position bandwidth of approximately 10 Hz and a positioning accuracy of approximately 25 μm. These stationary primaries serve as the guideway for the moving secondaries which function as the passive vehicles in the system, carry the material to be transferred, and have a minimum turning radius of approximately 1 m. A maximum velocity of 120 km/hr (33 m/s) and a maximum acceleration of 4 g (39 $\mathrm{m/s^2}$) would allow a tool to be delivered from a tool storage area to a machine tool 25 m away in approximately 3 s, a relatively short period of time compared to workpiece machining times. To achieve this high level of responsiveness, a system-level control is required that will allow propulsion units to cooperate in performing system functions such as dispatching, routing, and control of vehicles in real-time. While the cost of a system consisting of many stationary LIM propulsion units may be high, Hahn and Sanders [8] have shown that these costs may be offset by significant potential savings associated with elimination of conventional tool handling systems, elimination of the need for tool scheduling, elimination of conventional tool-changing and tool-storage hardware on machine tools, and reduction in the total number of cutting tools in the factory.

It is necessary to make control decisions very quickly in these high-performance systems, and the information upon which decisions are based must propagate through the system even more quickly. This is particularly true because schedules and routes are planned in real-time rather than planned in advance. Similar needs have been recognized in city traffic control [9], freeway traffic control [10], railway traffic control [11], and air traffic control [12] where real-time control based on current conditions is required instead of off-line control based on averages of traffic density and velocity [13]. Recent research in intelligent vehicle highway systems (IVHS) has begun to identify and address some of these system-level control issues [14]–[17]. There are significant differences, however, between the control requirements of the material transfer system considered in this paper and those of IVHS:

- There is at most one vehicle per system controller in the material handling system, but many vehicles per system controller in IVHS;

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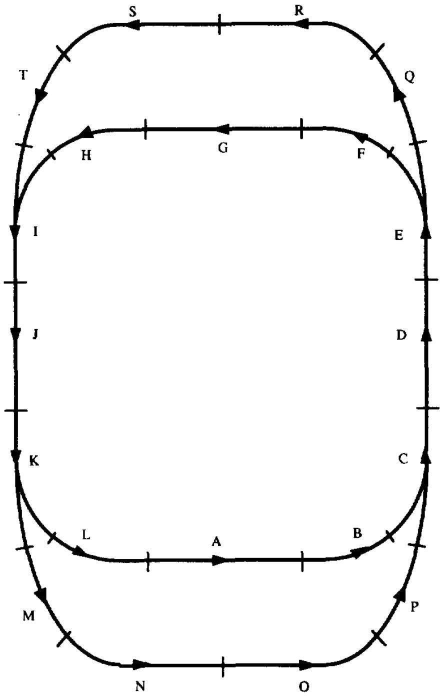

Fig. 1. Example of a small network of propulsion units.

- The L/V (propulsion unit length/maximum vehicle velocity) time characteristic is very short (a fraction of a second) in the material handling system, but relatively long (minutes) in IVHS;
- The vehicle length (0.25 m) is on the same order of magnitude as the propulsion unit length (1 m) in the material handling system, but orders of magnitude smaller (meters versus kilometers) in IVHS;
- The vehicle density is low and vehicles are independently controlled in the material handling system, but vehicle density is high and vehicles travel together in platoons for long periods of time in IVHS; and
- Unlike vehicles in IVHS, vehicles in the material handling system are passive and carry no sensor, power conversion, computer-based control "intelligence," or communication components.

The potential need to control thousands of propulsion units in a system where a vehicle under full closed-loop physical state control (position, velocity, acceleration) can pass through a propulsion unit in less than 0.1 seconds has a considerable impact on system design and leads to a choice of highly distributed, decentralized system-level control architectures. This tends to result in increased flexibility, modifiability, and fault tolerance. Single point failures associated with a centralized controller are eliminated [11], [18], and computing loads are distributed that otherwise tend to increase rapidly with number of vehicles and limit responsiveness in centralized systems [19]. Important differences between this type of architecture and the hierarchical architectures proposed for IVHS [14] are as follows:

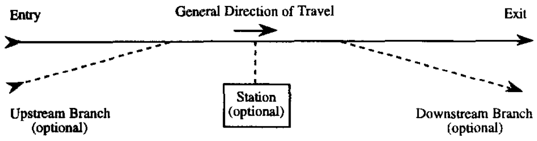

Fig. 2. Generic form of a propulsion unit.

- Physical control and system level control (routing and dispatching) are integrated at the vehicle level rather than separated in a hierarchy of levels;
- No central database is maintained for system topography, dimensions, vehicle states, etc.; and
- No "master-slave" relationships are implemented between vehicles as opposed to a strong master-slave relationship between platoon leader and followers.

In the following sections, a highly distributed control architecture for automated transport systems is described in which system-level control is achieved by embedding an identical control intelligence in each of the propulsion units in the network that makes up the guideways in the system. A generalized propulsion unit configuration is defined first along with a control information communication network that is topographically identical to the physical propulsion unit network. Next, a real-time parallel routing algorithm is described for finding the shortest route through the guideway network without a "map" of the network topography that enables autonomous nearest-available-vehicle dispatching. It is then shown that communication through the propulsion unit network can be used to cooperatively control multiple vehicles so that they operate in a safe manner and avoid collisions. Finally, results obtained from an experimental material handling system are used to make an assessment of the feasibility of application of the generic concepts developed to fully-distributed control of a high-performance material transportation system.

II. PROPULSION AND COMMUNICATION NETWORKS

Fig. 1 shows an example of a small network of propulsion units of the generic form shown in Fig. 2. When controlled using the fully-distributed control architecture shown in Fig. 3, there is no central system-level controller and the propulsion units cooperate through communication to perform all system-level vehicle-control functions. If the mechanical connections between propulsion units are identical to the communication connections, then the topographies of the propulsion and communication networks are identical. This property eliminates the need for global topography information because of the similarities between flow of vehicles from unit to unit and the flow of information from unit to unit. The flow of vehicles may be orders of magnitude slower than the flow of information, but the routing algorithms can be nearly identical.

Control of each passive vehicle in the fully distributed system can be individually achieved by transferring a "floating" vehicle controller from propulsion unit to propulsion unit along with the vehicle as it moves through the propulsion network. This is physically accomplished by having a copy of vehicle control software in each propulsion unit, and transferring

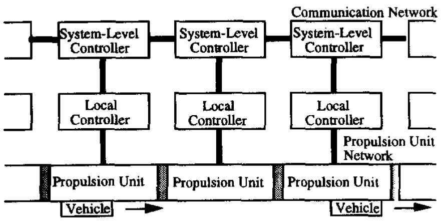

Fig. 3. Distributed system-level control of a propulsion unit network.

control from propulsion unit to propulsion unit along with the vehicle. Propagating vehicle state information both upstream and downstream from a vehicle allows other floating vehicle controllers to sense the state of nearby vehicles for purposes of collision avoidance. Messages broadcast upstream from a station will encounter vehicles moving through the network, some of which may be available to provide the service requested. The associated floating vehicle controller can send a response back downstream to the station, forming the basis for dispatching and routing.

Fig. 4 shows the upstream broadcast route of a message originating in Propulsion Unit A in the network shown in Fig. 1. Unit A sends the message to upstream to Unit L which sends the message upstream to Unit K. Unit K sends the message upstream to Unit J, but not downstream to Unit M. The message is sent from Unit J to Unit I and then to both Unit H and Unit T, travelling against the general direction of vehicle flow. Likewise, a message broadcast downstream from Unit A would be sent first to Unit B and then propagate downstream, travelling through units in the general direction of vehicle flow. Multiple routes through the system can result in multiple copies of the message arriving at a given propulsion unit, enabling shortest-route determination and nearest-vehicle dispatching based on order of arrival or accumulated distance transmitted. As the message travels from unit to unit, a routing list can be developed to which the name of each successive unit is appended. Examples of routing information appended to a message at various stages of progress through the network are shown in Fig. 4.

When a unit receives a message, it can first check to see if its name is already on the routing list. If it is, it has already received the message and the message is discarded, breaking loops in the network. If it is not, it adds its name to the end of the list and sends the message to the next unit. The ability to append additional information such as propulsion unit length to a message is also illustrated. This information can be used by other units in calculating travel times, vehicle motion profiles, and distances to other vehicles. In large networks, the information appended at each unit could accumulate excessively, affecting communication performance and implementation feasibility. When the number of branches is significantly less than the number of units, the routing list can be significantly abbreviated by appending only the current unit, the unit traversed at each branch, the originating unit, and the distance between units. The number of messages transmitted can be reduced, if desired, by restricting message propagation on some branches and limiting the distance that messages are allowed to propagate. This broadcasting algorithm has the following important properties:

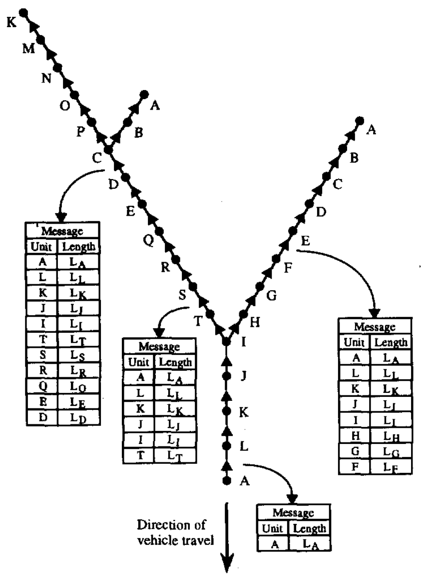

Fig. 4. Routing message propagation in an upstream broadcast.

- The network topology is determined dynamically;
- The message propagation path forms a tree rooted at the source;
- The number of messages generated is finite;
- Messages propagate through all possible routes only once;
- Messages propagate in parallel through different routes; and
- The number of message copies received is equal to the number of different routes.

III. Vehicle Dispatching and Routing

A protocol for vehicle dispatching is shown in Fig. 5. The propulsion unit at a source station searches for available vehicles in the network by broadcasting a message upstream containing a specification of the service required. When the floating controller of an available vehicle encounters the message, it can reply by transmitting a message containing the vehicle's name and capabilities downstream to the source station. The transmission can explicitly follow the route appended to the message that arrived from the source station, eliminating propagation of additional broadcast messages through the network. If the source station receives a reply from an available vehicle, it returns a message to the vehicle requesting a reservation. If the vehicle is still available and it receives the reservation request, it can accept the reservation by transmitting a confirmation message back to the station.

If a confirmation message has been received, a relationship between the source station and the vehicle has been established; otherwise the source station restarts the reservation process with another upstream broadcast of a request for service. In the former case, the relationship will continue until the vehicle and its floating controller arrive at the source station's propulsion unit. All vehicles can receive all requests for service

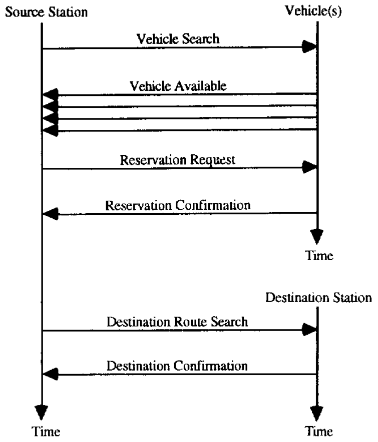

Fig. 5. Vehicle dispatching and routing protocol.

and all available vehicles can respond to all requests; therefore, source stations may receive responses from multiple available vehicles, and available vehicles may respond to requests from multiple stations desiring service. A source station may simply respond to the first available vehicle message received, or may apply more complex decision making in selecting a vehicle. Vehicle controllers and source units are not required to respond to any of the messages they receive and do not assume that they will receive a response.

The route that a reserved vehicle is to follow to the propulsion unit at the source station is appended to the reservation request message. Likewise, the route from the source station to the destination station can be found by broadcasting a destination route search message downstream. When this message reaches the propulsion unit at the destination station, the destination station returns a confirming message to the source station containing the route to be followed. The destination station may receive as many copies of the destination search message as there are routes between the source station and the destination station; but, it can discard all copies of the message except the copy that arrived by the shortest route as determined from the sum of propulsion unit lengths appended to the message as shown in Fig. 4. Alternatively, the destination station can use the first route search message it receives. This is the shortest route if all propulsion unit lengths and propagation delays in the system are equal, making the route search time independent of network complexity because the various message copies propagate in parallel, ensuring that search time is minimal compared to a sequential search [20].

Global information is minimized by acquiring routing information in real-time in messages and limiting the system to simple relationships that are easy to break and not preplanned [21]. This tends to lead to improved fault tolerance, reduced complexity, and reduced system development cost. The system is self-configuring and self-reconfiguring. A vehicle is implicitly included in the system if its floating controller is able to communicate with and make reservations with client stations. If it is removed from the system, it no longer responds to the messages and is thereby implicitly excluded from the system. Likewise, the network can be expanded by adding new propulsion units and stations that are implicitly integrated into the system when linked in the communication network.

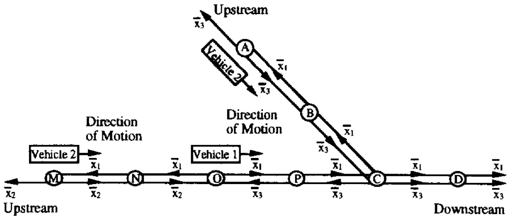

Fig. 6. Example of vehicle state communication.

IV. Cooperation Between Vehicles

If each floating vehicle controller in the network continually transmits the physical state of its vehicle (position, velocity, acceleration) both upstream and downstream in the network, then the controllers of both leading, following, and merging vehicles will continually receive this physical state information. This allows vehicles to cooperate by continually exchanging state messages, using appropriate control algorithms to maintain safe separation distances and velocities based on vehicle states, and making joint decisions to ensure safe operation and avoidance of collisions. The result is well-defined interactions between vehicles even though control is fully distributed and there is no on-board sensing of other vehicles. Fig. 6 shows an example of the flow of vehicle state information in the network shown in Fig. 1. Three vehicles are shown with states $\overline{x}_1, \overline{x}_2$, and $\overline{x}_3$. Copies of vehicle state messages must be transmitted both upstream and downstream at each propulsion unit with branches in the network so that vehicles can sense and react to the presence of vehicles in other branches of the network. For example, when a vehicle state message propagating downstream from Vehicle 1 reaches Unit C, a copy must continue to propagate downstream while also propagating upstream toward Vehicle 3. To reduce communication requirements, these vehicle state messages can be disposed of when they reach another vehicle or have traveled a specified maximum distance. The safety of the transportation network is clearly dependent on the reliability of communication and the ability to propagate large numbers of messages through the communication network at velocities that are orders of magnitude greater than vehicle velocities. The feasibility implementation of such a communication network for the automated material transfer system is analyzed in the following section.

V. Automated Material Transfer System

LIM propulsion unit prototypes for high-performance material transfer system described earlier in this paper have been constructed and tested at the University of Wisconsin-Madison, and research is continuing in their control and integration into larger systems [7], [22]. The communication rates required between propulsion units and the computational load imposed by communication and control are key factors affecting the feasibility of the concept, and an experimental physical model of the material transfer system therefore was constructed to establish communication and computation requirements for fully-distributed system-level control of this class of system. The communication, routing, dispatching, and collision avoidance concepts described above were implemented and verified in this experimental system which consisted of a network of 11 physical propulsion units and 11 copies of propulsion unit software sharing a single 33 MHz 80386 microprocessor [23]. Two vehicles were present in the system, each driven by an on-board dc motor powered at voltages commanded by propulsion unit software. Each vehicle was approximately 0.25 m in length and was capable of a maximum velocity of approximately 3.6 Km/hr (1 m/s). The length of the propulsion units was approximately 1 m, resulting in an L/V time characteristic of approximately 1 s, a factor of 33 larger than the L/V of 0.03 s specified for the automated material transfer system. Control computations were performed and vehicle state messages were transferred between propulsion units once every 0.1 s, 10 times faster than the 1 s L/V time characteristic of the experimental system, but 100 times slower than the 0.001 s specified for the automated material transfer system.

A. *Communication Rates*

At a maximum velocity of 120 km/hr, vehicles in the automated material transfer system traverse a 1 m propulsion unit in 0.03 s, and with a peak deceleration of 4 g, the minimum stopping distance is about 14 m (14 propulsion units). If it is desired to be able to reserve a vehicle greater than 14 m away from the source station within the 0.03 s minimum time it takes a vehicle to traverse one propulsion unit, then the four vehicle search and reservation messages shown in Fig. 5 must be transmitted from unit to unit at a rate of more than 1900 reservation-routing messages per second. Because it is expected that reservation-routing messages are sent relatively infrequently, it is reasonable to assume that at most one of these messages is interleaved between two consecutive vehicle state messages. For a vehicle state control loop-closure rate of 1000 Hz in the propulsion units, approximately 1000 vehicle state messages per second need to be transmitted if the density of vehicles in the network is low. The rate of message transmissions between propulsion units is therefore approximately 2000 messages per second ($T_c = 0.0005$ s). This is more than an order of magnitude greater than the 33 propulsion unit per second maximum velocity of the vehicles. The maximum message size for the automated material transfer system was estimated to be 212 bytes using results obtained from the experimental system. At 2000 messages per second and 212 bytes per message, a bit transmission rate of approximately 4 Mbits per second therefore would be required in each direction in each branch of a propulsion unit.

B. *Message Processing Load*

Each propulsion unit can have two entrances and two exits. If a peak rate of approximately 2000 vehicle state and reservation-routing messages per second can be received on each of these four possible branches and 1000 vehicle state messages per second can be generated by a propulsion unit if a vehicle is present, then the peak message processing rate for a propulsion unit is approximately 9000 messages per second. Approximately 50 μs were required to process each message received in the experimental system. Processing 9000 messages per second therefore would have consumed approximately 45% of the 33 MHz 80386 processor used in the experimental system, exclusive of byte transfers to I/O buffers.

C. *Computational Load*

The load on the 33 MHz 80386 microprocessor used in the experimental system was measured for various propulsion unit states. The maximum processor load for a single propulsion unit was found to be 3.4% of which 2.4% was associated with vehicle control and 1% was associated with message processing and overhead. The former was considered to be a good estimate of control computation load, but the latter could not be used to estimate communication load because messages were not externally transmitted by the single processor used in the experiment. The load of 2.4% for control computations at a 10 Hz rate for the 33 MHz 80386 microprocessor used in the experiment implies that performing control computations at a 1000 Hz rate in the automated material transfer system would have required 240% of the capability of this processor.

D. *Feasibility of Implementation*

The requirements for communication and control of the automated material transfer system have been estimated above to be a 4 Mbits per second per channel communication rate and a total load of 285% of a 33 MHz 80386 for control computations and message processing exclusive of byte transfers in communication. It is likely that these requirements can be met using state-of-the-art microprocessor technology. For example, the commercially-available T9000 Transputer has approximately 2000% more computing capability than a 33 MHz 80386 and has four bi-directional communication links and communication processors capable of transmitting 100 Mbits per second in each direction and performing byte transfers in parallel with other computations [24], [25]. On the other hand, the need for computing and communication in thousands of propulsion units may make it economically feasible to use a specially designed processors [26] to satisfy the communication requirements of the high-performance automated material transfer system.

VI. CONCLUSION

A fully-distributed system-level control architecture for dispatching, routing, and collision avoidance of multiple passive vehicles moving in a guideway network formed by a multitude of propulsion units has been described in this paper. The approach appears to be well-suited for systems in which the vehicle and propulsion-unit lengths are on the same order of magnitude and the propulsion-unit-length/vehicle-velocity time characteristic is small. It is necessary to make control decisions very quickly in these high-performance systems, and the information upon which decisions are based must propagate through the system even more quickly. This is particularly true when schedules and routes are planned in real-time rather than planned in advance. In the real-time, parallel, shortest route algorithm that has been developed the shortest route search time is independent of the network size. The algorithm does not require a global map of the transportation network, resulting in a self-configuring system and an opportunity to simplify the system and its development by eliminating global information. The propulsion network and communication network are unified in the approach as are system-level and physical vehicle control. The objective is to enable realization of high-performance systems by combining high vehicle speeds and short response times with self-configuring, extensible, fully distributed control.

The developments reported have been motivated by the need to design a system-level control for high-performance automated material transfer system where short propulsion unit lengths and high vehicle velocities require high computation and communication performance in the propulsion units that collectively control the system in a fully distributed manner with no central supervision. An analysis of the routing algorithm and flow of vehicle state messages using a experimental physical scale model has established communication and computation requirements what is believed to be a conservative verification of the feasibility of the concepts developed. The ability to rapidly respond to spontaneous requests for material transfer, the flexibility of guideway topography that can be achieved, and the high-performance position serving capability for individual vehicles offers new opportunities for manufacturing that may have a significant impact on factory equipment and organization as well as production scheduling and control. Furthermore, the unique nature of these LIM-based vehicle propulsion systems presents challenges in integrating electromagnetics, mechanical design and control to achieve the precision, high-performance control required for operation at high speeds and in close proximity to other vehicles.

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