RCS: A Reference Model Architecture for Intelligent Vehicle and Highway Systems

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Abstract

The Real-time Control System (RCS), developed over a period of two decades at the National Institute of Standards and Technology, is a reference model architecture for real-time intelligent control systems. It has been applied to automated manufacturing systems, space station telerobotics, unmanned land vehicles, multiple autonomous undersea vehicles, post office automation, and submarine operational automation systems. RCS defines a real-time hierarchical control structure that can be used to model and control arbitrarily large numbers of actuators; to integrate information from arbitrarily large numbers of sensors; and represent knowledge about the world at multiple levels of resolution. RCS partitions an intelligent control system into layers of sensory processing, world modeling, and planning/control modules. These are interconnected to each other and to a knowledge base by a communication system. Design tools and software development methodologies developed for RCS may have great utility for creating the real-time hierarchical distributed control architecture needed for Intelligent Vehicle-Highway Systems.

Introduction

A Real-Time Control System (RCS) reference model architecture for intelligent control systems [1] has been used for the design and implementation of a wide variety of intelligent system applications, ranging from discrete parts manufacturing [2], to unmanned undersea [3] and ground [4] vehicles, space station telerobotics [5], coal mine automation [6], submarine operational automation systems, and post office automation [7].

The RCS reference model architecture defines hierarchical heterogeneous layers of control. Each layer has characteristic timing and bandwidth of sensory processing and servo control loops. Each layer also has characteristic range and resolution of world model maps, and characteristic spatial-temporal range and resolution of goals and plans. Typically there is an order of magnitude difference in timing, and in spatial range and resolution, between layers. Each layer also has characteristic entity types in symbolic object-oriented databases. Typically, entities at one level "are-part-of" entities at the next higher level, and "are-composed-of" entities at the next lower level.

Each layer consists of one or more computational nodes, and each node contains sensory processing (SP), world modeling (WM), and task decomposition (TD) modules. These modules are interconnected within the nodes and the nodes are interconnected within and between layers by a communications system that provides database services and message passing functions.

The sensory processing modules provide capabilities for data filtering, recursive estimation, correlation, convolution, integration, and detection functions in both spatial and temporal dimensions. The world model modules provide question answering services, modeling, simulation, and predictive capabilities, graphics image generation, and database management services such as remembering, forgetting, and maintaining "consists-of" and "is-part-of" relationships between symbolic entities at different levels. The task decomposition modules provide planning and problem solving functions, resource management, constraint resolution, and servo loop closure with bandwidth appropriate to the level.

Figure 1 shows an example of how the RCS reference model is being used as a control system architecture for the U.S. Army unmanned ground vehicle Robotics Testbed (RT). At the bottom of the hierarchy are actuators and sensors. Actuators are driven by the output of the level 1 TD servo modules. They consist of steering, brake, throttle, camera pan/tilt drives, and operator displays. Sensors provide input to the level 1 sensory processing SP modules. They consist of steering, brake, and throttle sensors, navigation sensors (speedometer, odometer, GPS, gyros, accelerometers), road roughness sensors, camera pan/tilt sensors, TV camera signals, laser scanner signals, and operator inputs.

At the top of the hierarchy in Figure 1, goals are input from some higher level controller to a group of vehicles. In the Group level (5), group goals are decomposed into vehicle goals for each vehicle in the group so as to conduct coordinated group maneuvers. In the Task level (4), individual vehicle goals are decomposed into subgoals for each subsystem. This decomposition process continues through the E-Move level (3) for path planning, the Primitive level (2) for vehicle dynamics, and Servo level (1) for actuator control. As a result of this entire process, drive signals are generated for each actuator that accomplish the highest level goal. Sensory feedback interacts with the goal decomposition process at each level, modifying the system behavior so that high level goals are accomplished despite perturbations and unexpected events in the environment.

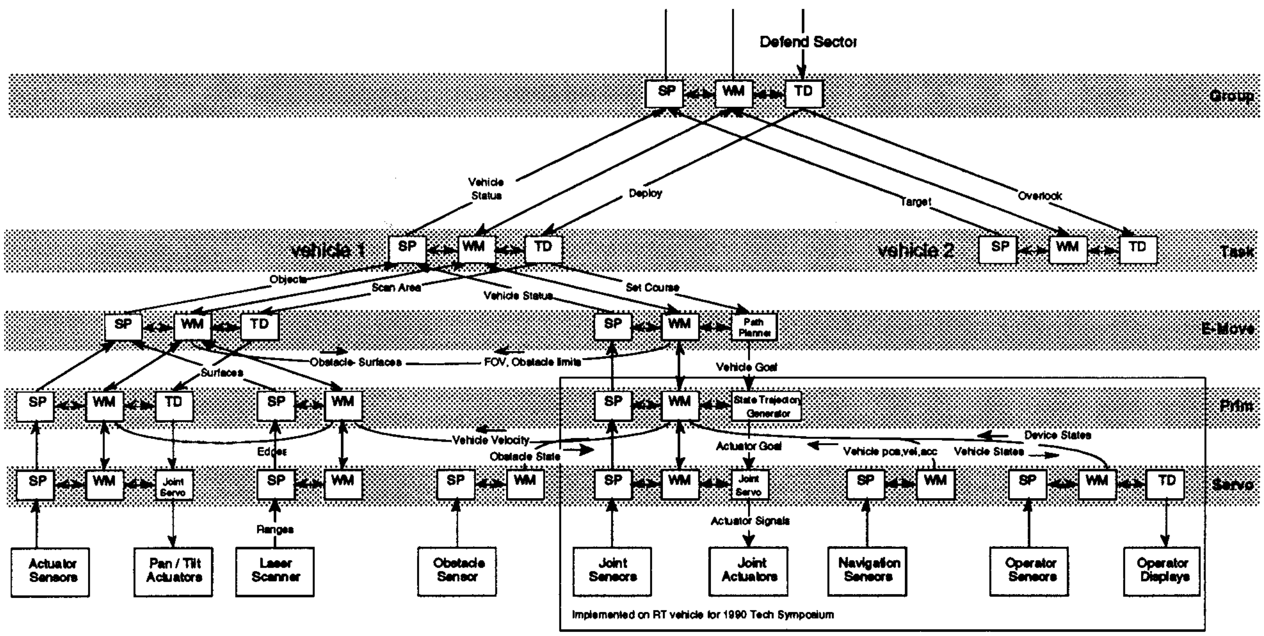

Figure 1. RCS reference model control architecture for the Army Robotics Testbed vehicle.

Figures 2 and 3 suggest how the RCS reference model architecture might be adopted for the design of an IVHS control system. There are two basic types of intelligent control systems required for IVHS. One is a control system for each vehicle. The second is a control system for the highway.

An IVHS Vehicle Control Architecture

Figure 2 illustrates an RCS architecture for the computer systems that reside in each vehicle. At each level of the vehicle control architecture, TD modules plan and control vehicle activities that carry out commands of the form <GOalong(map-path)TO(map-point)>. At each level in this control hierarchy, the commanded distance on the map and the time required to travel that distance is about an order of magnitude greater than at the level below -- while resolution in space and time is an order of magnitude less than at the level below. Similarly, at each higher level, feedback latency increases, and control bandwidth is reduced.

Figure 2 illustrates the type of map-paths and the average time to reach the goal map-point for each level of the vehicle TD hierarchy. The times and distances shown in Figure 2 and described below are chosen arbitrarily for purposes of illustration only. Real instances of times and distances are situation dependent.

Level 7 - Trip Destination Planning

Input to level 7 is the destination or goal and desired route for the vehicle for a period of up to 8 hours in the future. The task decomposition module at level 7 generates a plan for the next 8 hours consisting of a series of up to ten trip segments of about 50 minutes in duration. Maps in the level 7 world model have a range of 1000 km with resolution of 2 km. Entities consist of cities, states, major highways, interchanges, rest stops, and service areas. Sensory processing elements recognize or detect entities and verify current position on the map. Each step (trip segment) in the plan generated at level 7 becomes a destination, or goal, input to level 6.

An important feature of the RCS reference model architecture is that the functions of any TD module may be supplied by a human operator, or by an automatic vehicle controller, or by some combination of a human and computer system working interactively. For example, at level 7 of Figure 2, the WM module may simply display a map that a human can use to plan trip segments, or, the TD planning system may generate a plan which it displays for the human to approve or modify. Similarly, the human may execute the plan completely manually, or the TD task execution system may prompt the human operator at each critical point in the plan, or the TD system may execute the plan automatically with human override.

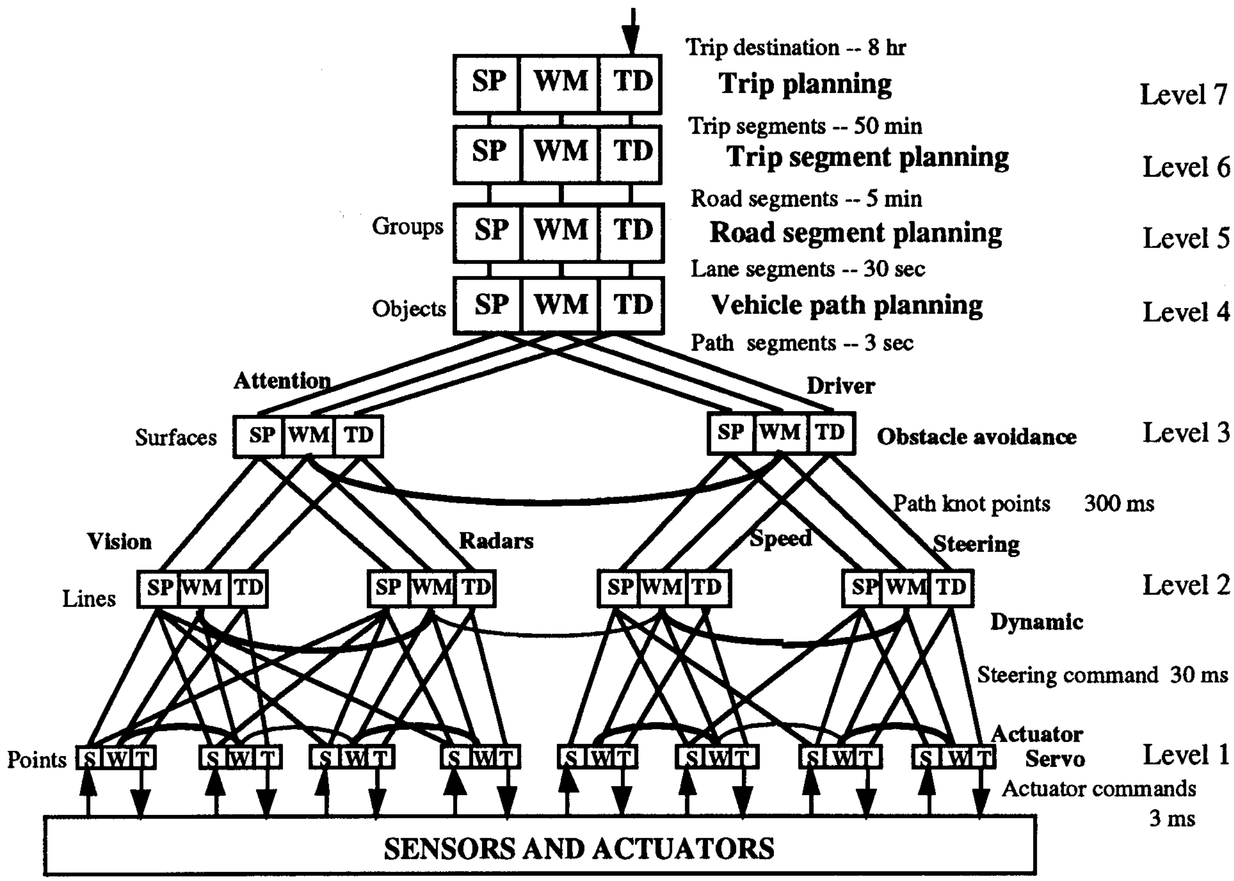

Figure 2. RCS reference model control architecture for IVHS vehicles. Control hierarchy for Advanced Vehicle Control System.

Level 6 - Trip Segment Planning

Input to level 6 defines the destination, or goal, that is desired for the vehicle about 50 minutes in the future. The task decomposition element at level 6 generates a plan for the next 50 minutes consisting of a series of about ten road segments of about 5 minutes in duration. Maps in the level 6 world model have a range of 100 km with resolution of 200 m. Entities consist of towns, secondary highways, road junctions, and major landmarks including interchanges, rest stops, motels, and restaurants. Sensory processing elements recognize entities and verify current position on the map. Each step (road segment) in the plan generated at level 6 becomes a destination, or goal input, to level 5.

Level 5 - Road Segment Planning

Input to level 5 is the destination, or goal, that is desired for the vehicle about 5 minutes in the future. The task decomposition element at level 5 generates a plan for the next 5 minutes consisting of a series of about ten lane segments of about 30 seconds in duration. Maps in the level 5 world model have a range of 10 km with resolution of 20 m. Entities consist of groups of vehicles, roads and streets, intersections, and neighborhood landmarks including rest stops, motels, and restaurants. Sensory processing elements recognize entities and verify current position on the map. Each step (lane segment) in the plan generated at level 5 becomes a destination, or goal input, to level 4.

Level 4 - Vehicle Path Planning

Input to level 4 is the destination, or goal, that is desired for the vehicle about 30 seconds in the future. The task decomposition element at level 4 generates a plan for the next 30 seconds consisting of a series of about ten vehicle path segments of about 3 seconds duration. Maps in the level 4 world model have a range of 1 km with resolution of 2 m. Entities consist of objects of interest such as nearby cars, trucks, pedestrians, trees, curbs, signs, traffic lights, parking places, and road markings. Sensory processing elements recognize entities and compute their attributes such as distance, velocity, and type of vehicles. Sensory processing also decodes the meaning of road signs and messages. Each step (vehicle path) in the plan generated at level 4 becomes a goal input to level 3.

Level 3 - Steering and Attention Coordination

Input to level 3 is the desired path for the vehicle for the next 3 seconds. The task decomposition element at level 3 generates a plan for the next 3 seconds consisting of a series of about ten steering movements of about 300 ms duration each. Maps in the level 4 world model have a range of 100 m with resolution of 200 mm. At level 3 and below, maps are warped into the perspective of the driver, so that objects on the map appear in proper viewing perspective to the driver. This enables maps generated by the world model to be overlaid on visual displays for the operator. Given the appropriate apparatus, heads-up displays could even overlay map information on the operator's view of the real world. World model entities consist of surfaces of attention such as the road surface, barriers, obstacles, and proximal surfaces of cars and trucks. Sensory processing elements recognize surface entities and compute their attributes such as distance, orientation, and vehicle clearance. Each step (steering movement) in the plan generated at level 3 becomes a goal input to level 2.

Level 2 - Steering Dynamics

Input to level 2 is the steering movement desired for the vehicle subsystem for the next 300 ms. The task decomposition element at level 2 generates a dynamically smooth steering movement consisting of a series of ten desired forces and torques acting on the vehicle chassis and sensor platforms over the 300 ms duration of the dynamic movement. Maps in the level 2 world model have a range of 10 m with resolution of 20 mm. Entities consist of lines and curves of interest such as lane markings and planned vehicle paths. Sensory processing elements recognize line and edge entities such as lane markings, road boundaries, and edges of obstacles. Each step in the plan generated at level 2 becomes a goal input to level 1.

Level 1 - Actuator Servos

Input to level 1 is the desired position of steering, throttle, and sensor platform actuators for the next 30 ms. The task decomposition elements at level 1 interpolate between each new desired position producing a plan for each actuator consisting of a series of ten actuator commands of 3 ms duration each. Each step in the plan generated at level 1 is compared with sensory feedback and used to generate a drive signal to an actuator once every 3 ms.

The actuators for each vehicle system are steering, throttle, and brake actuators, head lights, radar and infrared collision avoidance transmitters, communications transmitters, and camera pan/tilt/focus/iris/zoom actuators. Actuators also include visual displays and audio outputs for the operator, plus communications transmitters that convey vehicle identity and state, intended destination, route plans, etc. to the intelligent highway system.

Maps in the level 1 world model consist of display panels indicating vehicle state variables such as speed, tachometer, fuel, and oil pressure. Entities consist of state variables. Sensory processing elements scale and filter sensor data.

The sensors for each vehicle system are electromagnetic lane detectors, video and infrared cameras, radar receivers, and communications receivers. Intelligent vehicle sensors measure state variables such as the brightness, range, range-rate, and slew-rate of each pixel in the field of view. Received messages from highway transmitters may convey traffic conditions, road conditions, weather, speed limits, and suggested alternative routing.

An IVHS Highway Control System Architecture

While there is a control system of the type shown in Figure 2 in each vehicle (either in the form of a human operator, or an automatic system, or some combination of the two), there is also a control system for the highway system itself. A RCS reference model architecture for the IVHS highway control system is shown in Figure 3.

The actuators for the highway system are traffic lights, lane use indicators, programmable highway signs, radar transmitters, and communications transmitters. Communications transmitters may convey traffic conditions, road conditions, speed limits, and suggested alternative routing to each vehicle as it passes by.

The sensors for the highway system are magnetic loop detectors, video and infrared cameras, radar receivers, and communications receivers. Intelligent highway sensors measure state variables such as the position, velocity, and class of each vehicle as it passes through their field of view. Received messages from vehicles may convey identity, intended destination, planned routes, and other information about each vehicle, plus information about road and traffic conditions, and accidents.

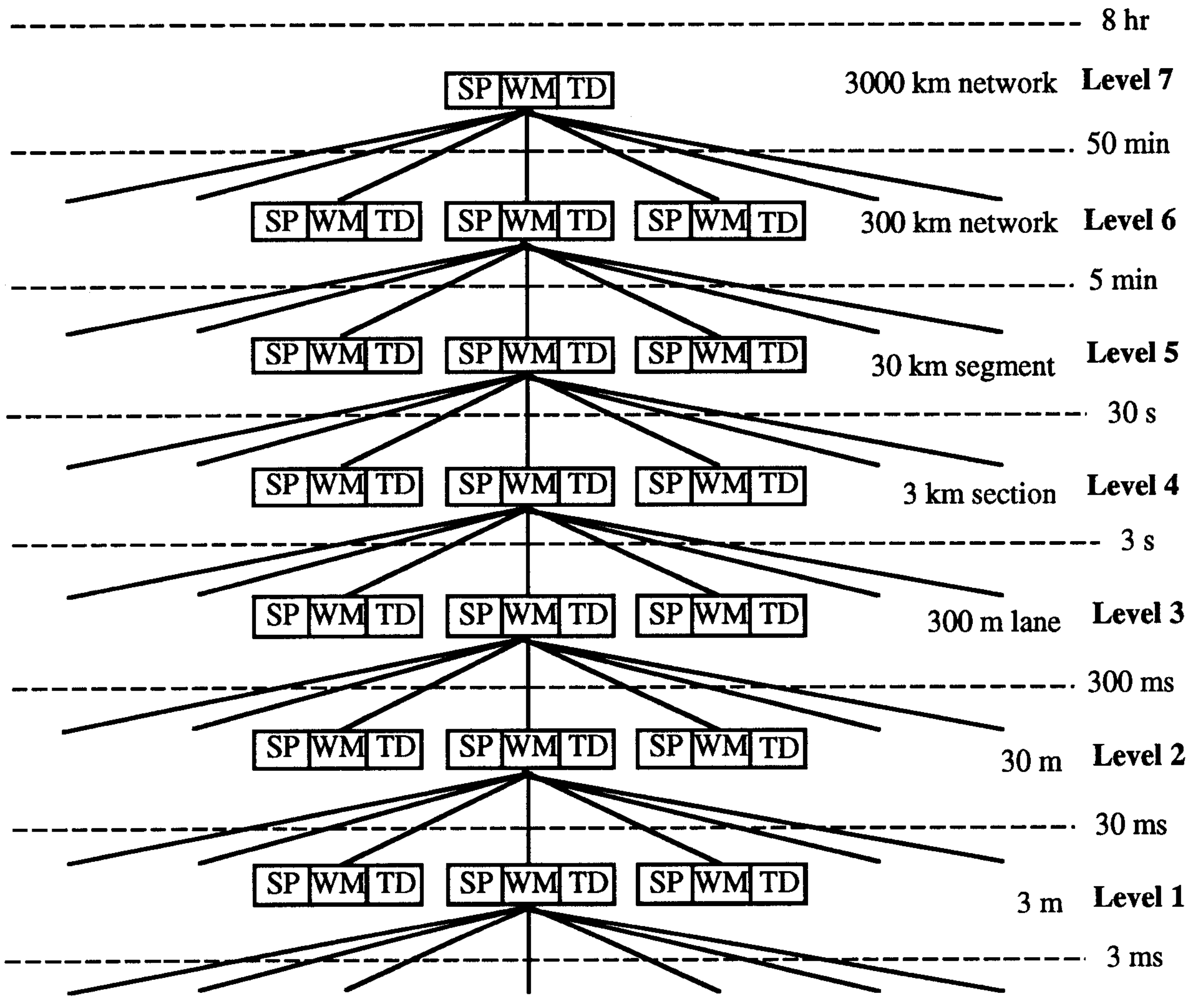

Figure 3. RCS reference model architecture for IVHS highway control system. A control hierarchy for the Advanced Traffic Management System and Advanced Traveler Information System.

In the example shown in Figure 3, the specific times and distances are representative only. Instantiation of the RCS reference model architecture for a specific IVHS system would reflect the specifics of the road network being modeled and controlled. The example in Figure 3 is of a road network 3000x3000 km in extent. Level 7 would be the highest level in such a system.

Level 7 - Highway System Control Center

The function of level 7 is to optimize throughput and safety for the entire highway system over an 8 hour period. The task decomposition module at the level 7 Highway System Control Center generates a plan consisting of a series of desired traffic density and flow rates of 50 minutes duration for each of its subordinate (level 6) highway regions. Each subgoal in the area plan generated at level 7 eventually becomes a region goal input to a region controller at level 6.

The WM map at level 7 consists of the entire 3000x3000 km road area network with resolution of 6 km highway segments. For each 6 km highway segment there is a map pixel database frame consisting of attribute-value pairs containing information such as current road and weather conditions, traffic density and flow velocity, a history of traffic density and flow velocity over the past 8 hours, and projected density and velocity over the next 8 hour period. These attribute values can be displayed on the level 7 map using colors, numerical symbols, or other information encoding techniques.

Sensory processing modules at level 7 compute area traffic statistics given inputs from all the level 6 region sensory processing modules over the past 8 hour period.

Note: As with the vehicle controllers, functionality at all levels of the RCS reference model architecture for the highway controller may reside in a human operator, in an automatic highway controller, or in some combination of the human and computer system working interactively. For example in Figure 3, the WM world model module may simply display a map that human operators can use to plan desired density and flow rates for the next lower level, or an automatic planning system may generate plans which a human operator approves or modifies.

Level 6 - Region Control

The function of each level 6 region control center is to optimize throughput and safety for that region over the next 50 minutes within the constraints imposed by the traffic density and flow rate goals input from level 7. Each level 6 task decomposition module generates a plan consisting of a series of about ten desired density and flow rates of about 5 minutes in duration for each of its subordinate level 5 (~ 30x30 km) highway network segments. Each subgoal in the region plan generated at level 6 eventually becomes a highway segment goal input to level 5.

Maps in the level 6 world model have a range of about 300x300 km with resolution of 600 m. For each 600 m highway segment there is a level 6 map pixel database frame containing information such as current road and weather conditions, traffic density and flow velocity, a history of density and flow over the past 50 minute interval, and projected density and velocity over the next 50 minute interval. These attribute values are displayed on the level 6 maps.

Sensory processing modules at level 6 compute region traffic statistics given input from all the level 5 segment sensory processing modules over the previous 50 minutes.

Level 5 - Segment Control

The function of each level 5 segment control center is to optimize throughput and safety for a 30 km segment within the constraints imposed by the desired density and traffic flow rate goals input from level 6. Each level 5 task decomposition module generates a plan consisting of a series of about ten desired density and flow rates of about 30 seconds in duration for each of its subordinate level 4 (~ 3 km) highway section controllers. Each subgoal in the segment plan generated at level 5 eventually becomes a goal to a level 4 section controller.

Maps in the level 5 world model have a range of about 30x30 km with resolution of 60 m. For each 60 m highway segment there is a level 5 map pixel database frame containing attribute-value pairs containing information such as current conditions, traffic density and average velocity, a history over the past 5 minutes, and projected density and velocity over the next 5 minute period.

Sensory processing modules at level 5 compute segment traffic statistics given input from all the level 4 section sensory processing modules over the past 5 minutes.

Level 4 - Road Section

The goal of each level 4 road section controller is to optimize throughput and safety for that road section within the constraints imposed by the desired density and traffic flow rates input from level 5. Each level 4 task decomposition module generates a plan consisting of a desired traffic density in each of its subordinate (level 3) lane controllers at 3 second intervals for 30 seconds into the future. Each of these desired traffic densities in the level 4 plan then becomes a goal for a lane controller at level 3.

Maps in the level 4 world model have a range of about 3x3 km with resolution of 6 m. This is sufficient resolution to represent individual vehicles. At this resolution, each map pixel can represent a 6 m x 1 lane piece of paved surface. Each map pixel can thus be represented by a database list, or frame, containing information such as whether or not that pixel is occupied by a vehicle, plus the identity, characteristics, and velocity of the occupant vehicle, a history of that occupant's position over the past 3 seconds, and prediction of that occupant's position over the next 3 second period.

Sensory processing modules at level 4 compute road section traffic statistics given input from all the level 3 lane sensory processing modules over the past 30 seconds.

Level 3 - Lane Control

The function of each level 3 lane controller is to control throughput and safety for that lane within the constraints imposed by the desired density and traffic flow rates input from level 4. Each level 3 lane controller modules generates a plan consisting of a series of about ten desired messages and signal control patterns at 300 millisecond intervals for each of its signal actuators.

Maps in the level 3 world model have a range of about 300 m with resolution of 0.6 m. For each 0.6 m map pixel there is a database frame indicating the presence or absence of a vehicle, its velocity, and perhaps its class and identity.

Sensory processing modules at level 3 detect the position, velocity, and inter-vehicle spacing for each vehicle given input from all the level 2 vehicle detection modules over the past 3 seconds.

Level 2 - Signal Control

The function of each level 2 signal controller is to produce the signals necessary to control traffic lights and generate the desired messages displays. Each level 2 task decomposition module generates control signals to lights and displays and formulates messages to be transmitted by level 1 communications transmitters.

Maps in the level 3 world model have a range of about 30 m with resolution of 60 mm. This range and resolution are comparable with TV camera images of highway scenes taken from overpasses or signal poles. TV images can be registered with maps of the roadway surface to compute the 3-D position of objects covered by each pixel in the image. Model matching image processing algorithms can then be used to automatically compute the 3-D velocities and trajectories of vehicles moving through the TV image. If desired (and if cost constraints permit), information from magnetic loop detectors and high bandwidth communications transponders can be correlated with pixels from TV cameras so that vehicle identity and characteristics can be overlaid on the visual TV camera displays.

Sensory processing modules at level 2 process images from cameras, radar detectors, and magnetic loop detectors so as to detect individual vehicles passing over loop detectors, or through the field of view of cameras or radio beams.

Level 1 - High Bandwidth Communications

The function of each level 1 controller is to modulate communications transmitters with messages for individual vehicles. There is no need for a world model at level 1. Sensory processing modules at level 1 demodulate signals from communications receivers.

Summary and Conclusions

The Real-time Control System (RCS) reference model architecture for intelligent control systems has been developed and used for a wide variety of applications including unmanned land vehicles. This paper suggests how RCS could be adapted for IVHS systems. Two types of control systems will be needed for IVHS systems -- one for vehicles, and a second for highways.

The RCS reference model defines a distributed real-time control architecture that allows for incremental, evolutionary, implementation. For example in the Robotics Testbed application illustrated in Figure 1, only part of the RCS architecture is currently being implemented. As the RT project evolves to greater degrees of autonomy and capability, the RCS reference model architecture will provide a road map for interfaces and module functional specifications.

The RCS reference model deals with system complexity through a systematic process of decomposition, first into levels of spatial and temporal range and resolution, and second into functions of sensory processing, world modeling, and task decomposition. Because of this modular approach, complex interactions such as might take place between the IVHS vehicle control system shown in Figure 2, and the highway control system shown in Figure 3, can be handled. For example, once the proposed system is operational each vehicle operator should be able to plan a trip and communicate that plan to the highway system. The highway system can then predict, based on all the plans, the density and throughput requirements for the highway system. If overloading is predicted, suggested alternative routing and time of travel estimates can be communicated back to the vehicles. If the vehicle operators accept the alternative routing, this can be communicated back to the highway system, and new predictions made. It is estimated that the amount of memory and computing capacity required at each computing node to implement the functionality described above will be within very reasonable cost limits in a few years.

Current research at the National Institute of Standards and Technology is directed toward developing an engineering methodology for intelligent control systems based on the RCS reference model architecture.

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