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Control System Architecture for TerraMax[1] – The off-road intelligent navigator

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Abstract – This paper proposes the architecture for real-time control of autonomous vehicle driving in a dynamic and uncertain off-road environment. It is applied on TerraMax intelligent off-road truck developed by OSU TerraMax team in Darpa grand challenge project. Conceived as hybrid, this architecture is composed of two layers: Situation Analysis and Logic layer, generally referred as high level intelligence, and Control and Execution layer, as low level realization. The separation of decision-making and actuation in this control architecture make its implementation applicable and robust in a dynamic and unknown environment. Situation based control decision is the key concept of the architecture. It can dynamically reschedule the current task or behavior of the truck. In our architecture, deliberation takes place at SAL while actuation is dealt through CE. Hence, the system is able to show a predictable response while keeping rapid reactivity to the dynamic environment. Copyright © 2002 IFAC

Keywords: autonomous vehicle, off-road, hybrid, control architecture

I. INTRODUCTION

Congress and the Department of Defense view unmanned vehicle technology as a critical element of our future military capabilities. The Grand Challenge is a bold effort to draw widespread attention to the technological issues associated with autonomous vehicles and to generate discontinuous breakthroughs in performance.

Many challenges must be overcome before autonomous ground vehicle (AGV) can drive off road effectively. Most pressing is sensing and modeling the terrain and planning safe paths through it while under the real-time physical constraints of a moving vehicle. Modern development in the fields of control, sensing, and communication has made complex and dedicated autonomous systems a reality. In a highly hazardous and unknown environment, the autonomy of the intelligent vehicle is key to a mission solution (Ozguner *et al*., 1997a). Control architecture is a framework that manages both the sensorial and actuator systems, thus enabling the vehicle to undertake a specified mission.

Lots of autonomous outdoor navigation systems have centered on local navigation tasks such as avoiding obstacles or path following. Global navigation has been limited to simple wandering, path tracking, etc. Those control systems were designed to operate and reason about all preplanned actions. The general idea was to sense the world, build a world model, plan actions with respect to goals, and then execute the plans via motor control systems. These systems were often brittle control systems incapable of operating in ever-changing environments because they required an accurate world model to reason properly about what to do. They are obviously insufficient for complex and unknown off road environments, where replanning may be needed to account for new information discovered in sensors and visual systems.

Rather than attempting to model the world, some system was designed with control intelligence that react directly to sensory information. It was referred as reactive system. In contrast to the planning system stated ahead, reactive system is built with multiple independent function modules. Each one is responsible for a particular task such as waypoint following, obstacle avoidance, car following, etc. according to the sensor related surrounding information. Reactive control system demonstrates real time navigation capability in complex environments. However, the ability of reactive system to achieve more long-term sophisticated goal seems limited.

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[1] Team TerraMax is an Oshkosh Truck Co. and Ohio State University partnership team with a technical alliance between OSU and University of Parma

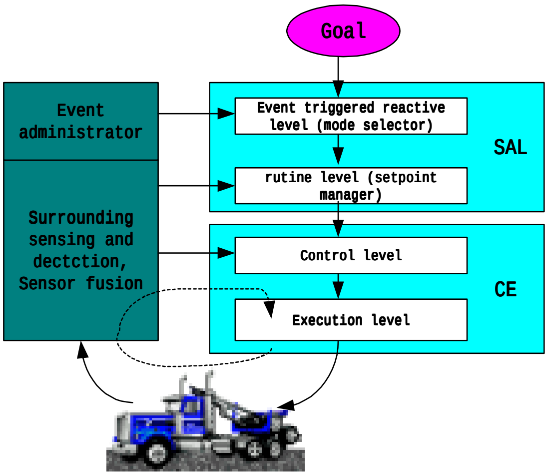

Figure 1. The general multi-level hybrid control architecture

The control system architectures for real-time autonomous intelligent vehicle have been developed and become more sophisticated in the last few years. To exploit the benefits of each approach, hybrid architecture takes advantage of the two previous architectures while minimizing their limitations and had demonstrated superiority with real-world capabilities. This architecture is generally composed of two main levels: 1) the deliberative routine level based on planning and 2) a functional level based on reactive behavior. These two level together forms the Situation Analysis and Logic (SAL) layer generally referred as high-level intelligence.

As the high-level intelligence works relative independently with world model, the achievement of the current operation goals such as path following and speed regulation are realized by an operative layer called Control and Execution layer (CE), referred as low level control. Thus, the autonomous truck is operated by the low level control via a group of actuators and sensors in a closed control loop given the trajectory and speed reference setpoints. The separation of SAL and CE enable robust control and fast performance of the truck in presence of all kind of nonlinearities and delays in the mechanical system. The whole control architecture is shown in figure 1.

The paper is organized as follows: section 2 introduces the system structure of TerraMax. Section 3 presents the intelligent hybrid control architecture of TerraMax and a conclusion is made in section 4.

II. SYSTEM STRUCTURE

The challenge vehicle (TerraMax) is based on an Oshkosh truck adjusted for drive-by-wire capability. The truck has six wheels, steering is accomplished with a servo motor turning the steering wheel, an actuator to move the brake pedal and direct electronic control of throttle and transmission.

The TerraMax control logic is make up of a number of blocks. Some of these are continually active, some become active when called. The established structure allows separate and somewhat independent development. It also allows continual expansion of different and more complex cases and situation to be addressed during the development cycle.

We are developing the following modules:

- Map and Route Planning Module
- Surround Sensing, State Sensing and Sensor Fusion
- High Level Terrain Classifier
- Situation/Control Logic
- Alarm
- Roll-back Analyzer
- Control and Execution Unit

The map and route-planning module creates database for map that provides weight and hospitability and accommodates real-time changes. Then it computes possible optimal and sub-optimal trajectories for the vehicle. This is the utility enabling preplanned action. Surround Sensing module consists a bunch of sensors and cameras. It will provide input for general Terrain Classification and make short distance and medium distance trajectory planning. State sensing and localization information come from INS/DGPS unit and sensor fusion (Redmill *et al.*, 2001). The whole world model is established with mapping, surrounding sensing and state sensing as shown in figure 2.

The vehicle receives and deals with all sensor data with the Surround Sensing/Sensor Fusion module. This includes GPS data, and all external and all internal sensors except the cameras. The cameras are dealt with separately by the Vision Module. Limit check are performed by the Alarm Module. The Alarm module also checks the “heartbeat” of all processors and furthermore monitors the timing and location bounds to see if the vehicle is “stuck”. The Alarm module can initiate appropriate action, ranging from adjusting sensor weights, operating conditions to initiating the Rollback Analysis Module. The Alarm Module will also check for excess deviation from the nominal path to ascertain that the low-level trajectory will not push vehicle out the route boundaries. All the information is further synthesized in high-level control layer and then operation command and reference setpoints are generated and feed to the low-level control and execution.

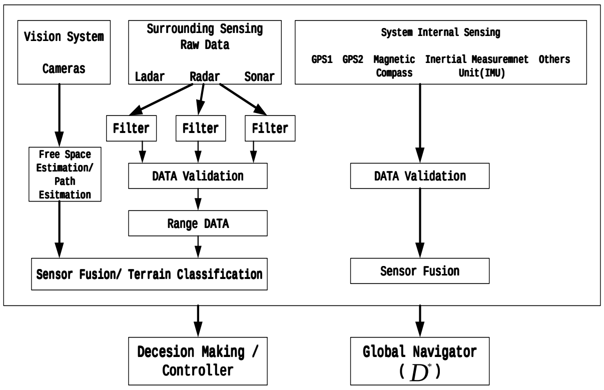

Figure 2. World modeling with Surround sensing/ sensor fusion

III. INTELLIGENT HYBRID CONTROL ARCHITECTURE

HIGHER LAYER

Tasks in driving can be divided into two levels: at the higher level, maneuvers such as lane changing and car following are determined to meet the objective of operation (e.g., a target arrival time) under the constraints imposed by the environment conditions. The high layer of intelligence is called Situation Analysis and Logic (SAL) layer. In real application, sensory information on which an autonomous vehicle makes decisions is uncertain (e.g., measurement error or occlusion). In addition, the situation is dynamic, i.e., the situation evolves as time elapses. Thus, the high level planning and decision should be based on the prediction of the future travel condition with consideration of uncertainty.

To make a plan with a long-term prediction tends to be computationally expensive if all factors are considered in every situation. Moreover, it may be inefficient to always carry out such a planning. Therefore, we propose three sub-levels in this layer: 1) Adaptor 2) Rule based drive mode selector and 3) Set point manager. While applying the set point manager to generate waypoint and reference speed setpoint adaptively based on surrounding world modeled, the other two level manager modes that is triggered only when it is necessary, for example, obstacle avoidance mode is set effective when obstacle is detected along the path way, according to both the history of maneuvers and the current surrounding conditions.

The main tasks for the high-level intelligence are: (1) to build the world model to express the pre-stored information and locally sensed information; (2) to generate proper reaction according to any model change, including some moving obstacles; and (3) to response to any expectable unexpected events, such as outer stop command and/or temporary failure of some sensors, etc.

To accomplish all these tasks faultlessly, the structure of the high-level intelligence includes three layers, from the input and output point of view. Based on the basic preplanning and reactive structure stated ahead. The whole system structure of the module is shown as in the figure 3.

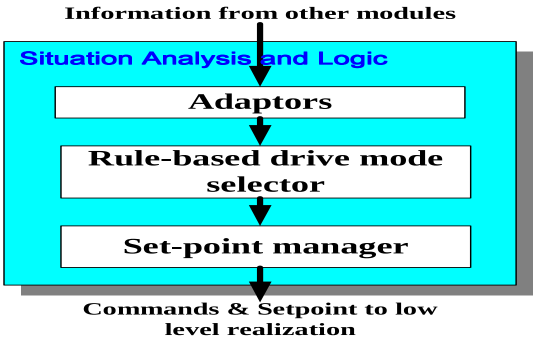

Figure 3. Structure of SAL

Some submodules in the first layer are called information adaptors, which adapt outer information generated from MAP Module, Sensor Fusion Module and Alarm Module for the inner world model to update accordingly. This layer also consists of submodules that check the status of the truck itself related to the environment around, so that the second layer, which is a finite state machine, could take suitable response. This can be formulated as:

$$M(k+1)=P(M(k),I(k),U(k)) \tag{1}$$

where *M(k)* represents the states of the world model including the state of the truck. *I(k)* represents the information that includes not only the current data obtained at step *k*, but also the historical data that obtained some certain number of steps before. *U(k)* is the control commands, including the historical commands *u(k), u(k-1), …*, which will be defined later. And *P(·)* is update law of the world model. This layer is called *the adaptors* layer in the structure.

The goal of the finite state machine in the second layer is to select proper drive model according to the world model and the update information come from the first layer. This can be formulated as:

$$X(k+1)=F(X(k),M(k)) \tag{2}$$

where $X(k)\in\Im=\{\text{AR, PK, RB, CF, RO}\}$ are the state of the state machine at step *k*. The set of states $\Im$ includes: Alarm Response (AR), Path Keeping (PK), Roll Back (RB), Car Following (CF) and Robotic Operation (RO). *M(k)* is from the first layer as defined before. And *F(·)* is state transition function, which decides the jump from one drive mode of the truck to another. The transition function is the key component in this intelligent layer, since it makes decisions rather than the controller parameters therefore determines directly how good the controller result could be. In TerraMax, the transition functions are defined by rules that are based on the fuzzification results of the inner world model, including the road condition, terrain classification, etc. Therefore, the second layer is called *rule-based drive mode selector*.

The third layer includes several controllers corresponding to each of the element, the drive modes, in the set $\Im$ defined before. Each drive mode controller is designed individually to respond both the *M(k)* and the change of *M(k)* by generating control commands accordingly, represented by:

$$u(k)=C_{X(k)}(M(k),I(k))=C(X(k),M(k),I(k)) \tag{3}$$

where *X(k),M(k),I(k)* are defined as before. $C_{X(k)}$ is the controller corresponding to the drive mode *X(k)*. *u(k)* is the control output of the high level intelligence. Some control algorithms are designed and studied in these controllers, including the obstacle avoidance algorithm. This control output is sent to the low level realization referring to the hierarchical hybrid structure of the control system in the TerraMax. In particular, the control output of the high level intelligence is the combination of command and parameters, speed set point and path points for the low level realization to follow by. Moreover, as far as the real-time physical constraints of the truck are considered, *u(k)* should satisfies some conditions so that the output is physical feasible for the truck and would not cause any dangerous results like roll over while make sharp turn at a high speed. So every control output should be verified before being sent to the low level. The third level is therefore called *set point manager*, since which generates the set points and verifies them.

The high-level intelligence module is tested repeatedly in our simulator and it works well so far. However, from the system test point of view, this system could never be test enough on one or several runs in simulator, even in the real tests, since the situation of off-road, the possible failure of equipments consists a huge uncertainty space. The following figure 4 is a successful run for the truck avoids obstacles sensed while keeps following the route and reached the final checkpoint.

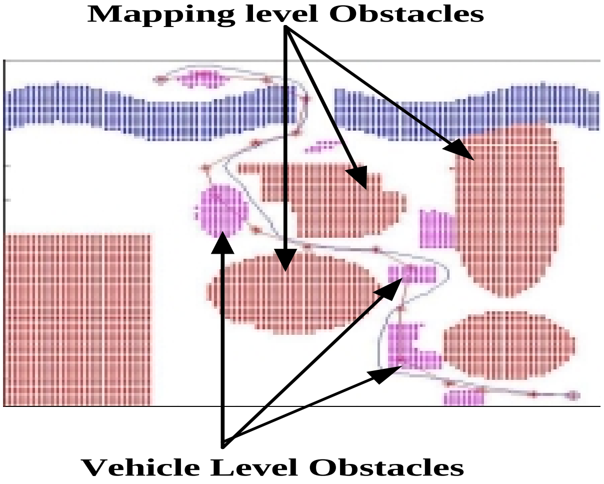

Figure 4. Simulation Result

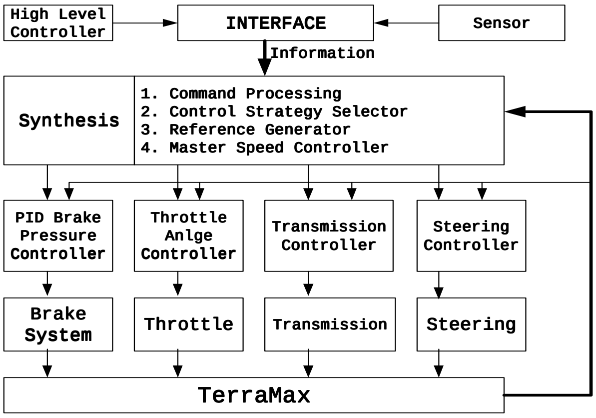

Figure 5. Low-level control structure

LOWER LAYER

At the lower layer, a selected maneuver from high layer intelligence is translated into actual control operations. As the high-level intelligence works relative independently with world model, the achievement of the current operation goals such as path following and speed regulation are realized by an operative layer called Control and Execution layer (CE), referred as low level control (Ozguner *et al*., 1997b). This layer is further divided into two sub-levels. The first or higher level is Control Level. The Control Level is in charge of the servo control of the autonomous truck including speed reference setpoint regulation and waypoint following (Ozguner *et al*., 1995)(Haskara et al., 1997)(Hatipolgul et al., 1997). For example, after get the mode command “car-following” from higher-layer intelligence, adaptive cruise control is activated in this level and will regulate the autonomous truck speed according to the relative position and speed relationship with a moving object and the speed setpoint from SAL.

The execution level contains sensor and actuator groups. This layer is responsible for the interface between truck hardware. Actuators are controlled to obtain the actuation aim translated from SAL. This level consists steering control, throttle control, braking regulator and transmission switch control. A general structure of the CE is shown in figure 5.

IV. CONCLUSION

This paper has proposed control architecture for autonomous off-road driving of TerraMax for Darpa Grand Challenge project. With its hybrid structure, this architecture is composed of two layers: Situation Analysis and Logic layer, generally referred as high level intelligence, and Control and Execution layer, as low level realization. The separation of decision-making and actuation in this control architecture make its implementation applicable and robust in a dynamic and unknown environment. Based on the mapped world model and the local surround sensing, it can adaptively reschedule the current task or behavior of the truck. In our architecture, deliberation takes place at SAL while actuation is dealt through CE. Hence, the system is able to show a predictable response while keeping rapid reactivity to the dynamic environment

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