Executing Reactive Behavior for Autonomous Navigation (Extended Abstract)

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Abstract

Complex problems, such as driving, can be solved more easily by decomposing them into smaller sub-problems, solving each sub-problem, and then integrating the solutions. In the case of an autonomous vehicle, the integrated system should be able to "react" in real time to a changing environment and to "reason" about ways to achieve its goals. This paper describes the approach taken on the UMass Mobile Perception Laboratory (MPL) to integrate independent processes (each solving a particular aspect of the navigation problem) into a fully capable autonomous vehicle.

1 Introduction

One of the goals of the autonomous vehicle effort at the University of Massachusetts is the development of a landmark-based navigation system capable of robust navigation both on-road and cross-country. The experimental laboratory vehicle for this effort is the Mobile Perception Lab (MPL) - a heavily modified Army HMMWV ambulance that is equipped with actuators and encoders for the throttle, steering and brake and passive sensors (Figure 1).

The task of autonomous navigation, as with many other complex tasks, can be decomposed into more specific subproblems like road following, obstacle avoidance and landmark recognition. In order to achieve a fully autonomous vehicle, the solutions to all these subproblems must be integrated into a coherent system. Since each of the subproblems is still a field

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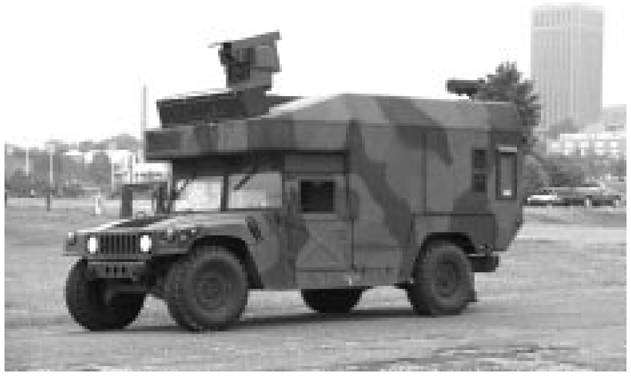

Figure 1: The Mobile Perception Laboratory, built on a modified HMMWV chassis, has computer controlled steering, throttle, and brakes, a complete research laboratory on the back.

of active research, in which approaches and solutions may change rapidly over time, it is important to provide an environment in which researchers can quickly experiment with different combinations and parameterizations of those modules. At the same time, MPL's software environment must be efficient enough to meet the demands of real-time navigation. This paper focuses on the preliminary work done on the problem of integration for the MPL.

2 What is a behavior?

In the robotics literature, the word *behavior* has generally been used to describe processes that connect perception to action, i.e., a behavior senses the environment and does something based on what was perceived. A combination of behaviors is also called a behavior, thus, a complex behavior can be achieved by combining simpler behaviors. In Brooks' subsumption architecture [3], the task of robot control is decomposed into levels of competence; each level, in combination with lower levels, defines a behavior. Payton, Rosenblatt and Keirsey [6] in their Distributed Architecture for Mobile Navigation system (DAMN), refer to behaviors as very low level decision-making processes which are guided by high level plans and combined through arbitration. In their DEDS work, Ramadge and Wonham [8], events are considered the alphabet, Σ, of a formal language; a behavior is a sequence of events, or a string over Σ^*. Note that in this terminology every prefix of a string is also a behavior, i.e., the sequential combination of behaviors is a behavior.

These definitions, although consistent, can be confusing - the same term is used for individual processes and for the composition of these processes. To make the distinction clear, we have chosen to think of a behavior as a *mode of operation* [6], in which several *perception-action processes* [9] are executed concurrently. Each process converts sensory data into some kind of action (either physical or cognitive), and at any time may generate an *event* - a signal to let the system know that "something" significant has occurred. All inter-process communication is achieved through a global *blackboard* - a section of shared memory accessible to all[1]. The system *reacts* to events by changing its behavior; hence the sequence of behaviors actually executed depends upon the sequence of events. Since the latter is unpredictable, so is the former. To program such a system, one must specify which processes constitute a behavior and for each possible event describe the system's reaction.

[1]In its current incarnation, the blackboard is built on top of the ISR3 - a symbolic real-time database for vision [2].

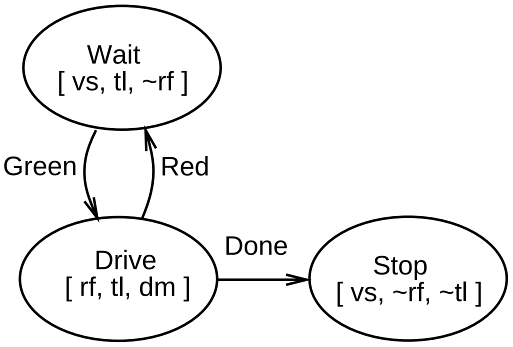

Figure 2: Script of a simple driving system: (a) Finite state machine (FSM) representation. Listed below the state name are the perception-action processes that should be run and killed (marked with a ˜) in that state. This example is composed of four perception-action processes: follow the road (*rf*), check for traffic lights (*tl*), monitor the distance traveled (*dm*), and stop the vehicle (*vs*).

We employ a finite state machine (FSM) - with states representing behaviors and transitions representing reactions to events - to specify the system. For example, consider the FSM in Figure 2. This system will drive on the road while obeying traffic lights, until a given distance is travelled.

Based on the notion of behaviors represented as states of a finite state machines, we have implemented a *Behavior Description Language* (BDL) [9]. Behaviors are described as two sets of perception-action processes, and a transition table. The *run* set specifies the minimum set of processes that form the behavior; the *kill* set specifies those processes that should not be running for the correct execution of the behavior. The transition table specifies what to do for each of the valid events (events not specified in the state description are not valid).

3 Scripts - Augmented finite state machines

In our model tasks are given to the system in terms of finite state machines. As the complexity of the vehicle's task grows, this approach may lead to long and repetitive representations (the `drive-100-meters` state would probably be very similar to the `drive-150-meters` state). To alleviate this problem, the FSM is augmented with a *fetch-goal* state, and the states are parameterized. A particular behavior (like drive for 100 meters or drive for 150 meters) is instantiated from this generic description through the use of blackboard messages at run time. The system starts in the *fetch-goal* state where it reads goals (in terms of states) from a precompiled *plan*. When a goal is retrieved, the relevant blackboard messages are written into the blackboard before enabling the perception-action processes. Once such a process is running, it looks for its parameters in the blackboard.

Formally, a *script* S is defined as the eight-tuple $(P, Q, E, M, \delta, \kappa, \rho, G)$, where:

- P is the set of available perception-action processes.
- Q is the set of states ($Q = B \cup$ *fetch-goal*, where B is the set of behaviors).
- E is the set of possible discrete events (transitions in the FSM).
- M is the set of valid blackboard messages.
- δ is the transition table, $\delta : B \times E \to Q$
- κ is the kill table, $\kappa : B \times P \to \{0, 1\}$
- ρ is the run table, $\rho : B \times P \to \{0, 1\}$
- G is the plan expressed in terms of subgoals. Each subgoal is of the form $< b_g, M_g >$, for $b_g \in B$ and $M_g \subseteq M$.

Scripts can be generated by an automated planner, or by hand (using BDL).

3.1 The script monitor

The *script monitor* in our system is in charge of "high level" control[2]: reading, interpreting, and executing BDL scripts. The monitor does not perform any action on the vehicle, instead it controls the set of running processes at any time.

The script monitor consists of two modules, an *interpreter* and an *executer*. The *interpreter* takes a BDL script S and builds the transition (δ), kill (κ) and run (ρ) tables; then the subgoals in S's plan are stacked into the *execution stack* G. The *executer* simulates a finite state machine as follows:

[2]In this context, "high level" control is used to differentiate the control of processes from the "low level" control of the vehicle actuators.

```
1. $b_g \leftarrow$ fetch-goal
2. if ($b_g =$ fetch-goal) then
   (a) if $G$ is empty then $\forall p \in P$
       i. kill($p$)
       ii. if ($\rho(b_g, p) = 1$) then run($p$)
       iii. stop
   (b) $< b_g, M_g > \leftarrow$ pop($G$)
   (c) blackboard $\leftarrow M_g$
3. $\forall p \in P$ if ($\kappa(b_g, p) = 1$) then kill($p$)
4. $\forall p \in P$ if ($\rho(b_g, p) = 1$) then run($p$)
5. Wait for an event $e \in E$
6. $b_g \leftarrow \delta(b_g, e)$
7. goto 2
```

Clearly, for the system to complete the task in G, the following must hold:

$$\forall b \in Q \;\; \exists s_b \in E^+ \;\; s.t. \;\; \hat{\delta}(b, s_b) = fetch - goal$$

where $\hat{\delta}$ is the transition function applied to a sequence of events.

4 An example

The following perception-action processes have been successfully tested on the MPL:

- Vehicle pose determination based on landmark model matching [1, 5].
- Neural-network road following (ALVINN) [7].
- Servo-based steering [4].
- Obstacle detection via stereo.
- Reflexive obstacle avoidance.
- A distance monitor.
- Turning via dead reckoning.

Theses processes were combined in a script to achieve the following:

1. Drive on the road, while avoiding obstacles, for x meters.

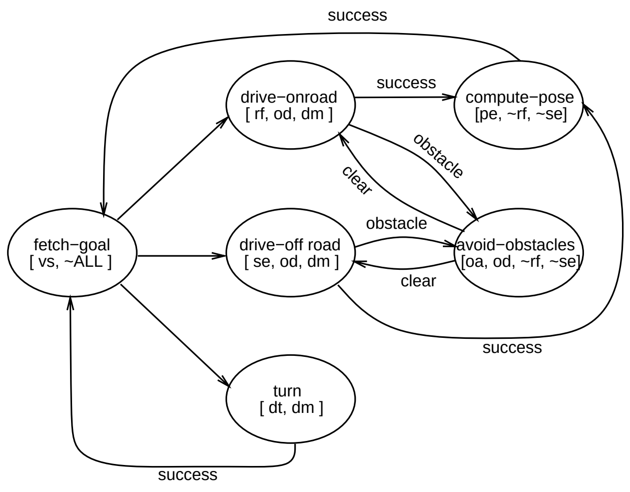

Figure 3: An augmented FSM for on/off road navigation : drive while avoiding obstacles for a specified distance, then check position. The perception-action processes involved include pose estimation (*pe*), road following (*rf*), obstacle detection (*od*), obstacle avoidance (*oa*), servoing (*se*), distance monitor (*dm*) and dead reckoning turning (*dt*).

2. Estimate vehicle position using landmarks.
3. Drive on the road, while avoiding obstacles, for y meters.
4. Estimate vehicle position using landmarks.
5. Turn left (at the experimental site this command is a transition to off-road navigation).
6. Drive off road, while avoiding obstacles, for z meters.

5 Conclusions

An autonomous vehicle should be able to react in real-time to a changing environment, but it should also be able to reason about its goals. In our system, these seemingly contradictory capabilities are achieved through the use of a"programable" finite state machine. In this model, reactions to events (either internal or external) are represented as state transitions. The system can react rapidly by following a transition table. Goal-directed reasoning is supported by the "programability" of the FSM - the system does not enforce what goes into a state or a particular transition table, instead it executes "scripts" which eventually will be written by an automated planner.

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