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ABSTRACT

Vehicle control in a-priori unknown, unpredictable, and dynamic environments requires many calculational and reasoning schemes to operate on the basis of very imprecise, incomplete, or unreliable data. For such systems, in which all the uncertainties can not be engineered away, approximate reasoning may provide an alternative to the complexity and computational requirements of conventional uncertainty analysis and propagation techniques. Two types of computer boards including custom-designed VLSI chips have been developed to add a fuzzy inferencing capability to real-time control systems. All inferencing rules on a chip are processed in parallel, allowing execution of the entire rule base in about 30 μsec (i.e., at rates much faster than sensor data acquisition), and therefore, making control of "reflex-type" of motions envisionable. The use of these boards and the approach using superposition of elemental sensor-based behaviors for the development of qualitative reasoning schemes emulating human-like navigation in a-priori unknown environments are first discussed. We then describe how the human-like navigation scheme implemented on one of the qualitative inferencing boards was installed on a test-bed platform to investigate two control modes for driving a car in a-priori unknown environments on the basis of sparse and imprecise sensor data. In the first mode, the car navigates fully autonomously, while in the second mode, the system acts as a driver's aid providing the driver with linguistic (fuzzy) commands to turn left or right and speed up or slow down depending on the obstacles perceived by the sensors. Experiments with both modes of control are described in which the system uses only three acoustic range (sonar) sensor channels to perceive the environment. Simulation results as well as indoors and outdoors experiments are presented and discussed to illustrate the feasibility and robustness of autonomous navigation and/or safety enhancing driver's aid using the new fuzzy inferencing hardware system and some human-like reasoning schemes which may include as little as six elemental behaviors embodied in fourteen qualitative rules.

1. INTRODUCTION

One of the greatest challenges in developing motion planning and control systems for vehicles operating in a-priori unknown, unpredictable, and dynamic environments is to design the methods for handling the many imprecisions, inaccuracies, and uncertainties that are present and pervasive in the perception and reasoning modules. These imprecisions typically are caused by: (1) errors in the sensor data (current sensor systems are far from perfect) which lead to inaccuracies and uncertainties in the representation of the environment, the robot's estimated position, etc., (2) imprecisions or lack of knowledge in our understanding of the system, i.e., we are unable to generate complete and exact (crisp) mathematical and/or numerical descriptions of all the phenomena contributing to the environment's and/or the system's behavior, and (3) approximations and imprecisions in the information processing schemes (e.g., discretization, numerical truncation, convergence thresholds, etc.) that are used to build environmental models and to generate decisions or control output signals. In such systems, for which it is not currently feasible to fully engineer all the uncertainties away from the perception subsystems, approximate (or "qualitative") reasoning may provide an alternative to the complexity and prohibitive computational requirements of conventional uncertainty analysis and propagation techniques.

In cooperation with MCNC, Inc. and the University of North Carolina, two types of VME-bus-compatible computer boards including custom-designed VLSI chips have been developed to add a qualitative reasoning capability to real-time control systems [1],[2],[3],[4]. The methodologies embodied on the VLSI hardware utilize the Fuzzy Set Theoretic operations [5],[6],[7],[8] to implement a production rule type of inferencing on input and output variables that can directly be specified as qualitative variables through membership functions. All rules on a chip are processed in parallel, allowing full execution of the rule base in about 30 μsec. This extremely short time of operation makes real-time reasoning feasible at speeds much faster than typical sensor data acquisition rates, therefore, making envisionable the control of very fast processes such as sensor-based "reflex-type" motions.

The basic operation of these boards and a formalism merging the fuzzy and behaviorist theories for the development of qualitative reasoning schemes emulating human-like navigation have been discussed in [4]. The approach using superposition of elemental sensor-based fuzzy behaviors has been shown to allow easy development and testing of the inferencing rule base, while providing for progressive addition of behaviors to resolve situations of increasing complexity. This fuzzy behavior formalism has been used to demonstrate the feasibility of autonomous robot navigation in a-priori unknown environments on the basis of sparse and very imprecise sensor data [9]. For these feasibility experiments, a small omnidirectional robotic platform prototype [10] equipped with a ring of acoustic range finders (sonars) was used in a laboratory environment. In this paper, we present further developments on the feasibility of autonomous navigation in a-priori unknown environments using approximate reasoning and very inaccurate sensor data. Section 2 describes how the "human-like reasoning" navigation rule base of the small omnidirectional platform was extended to allow for the kinematic limitations of a car (non-holonomic and steering constraints) and was applied to the autonomous navigation of a car in laboratory simulations. The operation of the system in driver's aid mode is also described in this section. The entire perception and fuzzy inferencing system was then positioned on a car and Section 3 presents the operation of the system in outdoor environments. The last section discusses the results of these feasibility studies and presents the concluding remarks.

2. FUZZY BEHAVIORS FOR CAR DRIVING

In the experiments with the small omnidirectional platform, fuzzy rule bases embodying six basic navigation behaviors [9] were developed to control the turn rate (TR) and the translational speed (TS) of the platform as a function of the goal direction (GD) and obstacle proximity (OP). The single chip board [1] was used which allows inferencing on four input variables to produce two output variables. The four input variables were selected as the goal direction and obstacle proximity in sectors at the left, center, and right of the travel direction. As shown on Fig. 1, each sector encompasses five sonars. In each sector, the distance returns from each of the five sonars are weighed by a factor proportional to their firing direction, and the smallest value is utilized to indicate obstacle proximity within the sector. Effectively, this corresponds to giving the platform the equivalent of three "very wide and blurry" eyes. The navigation goal can be specified in the current system as a goal point or as a heading to be maintained. When the goal is a point, the odometry system updates the position of the robot at each loop rate and calculates the relative direction to the goal point as input to the inferencing system. When the goal is a heading, a compass is used to directly provide the relative goal direction as the difference between the platform current heading and the goal heading. As explained in [4], membership functions representing the levels of uncertainty with which the values were obtained are applied to the four input values. Very robust navigation characteristics were obtained in the laboratory experiments using these very sparse and imprecise sensor data (purposefully selected as such to emphasize the feasibility demonstration), and as little as fourteen fuzzy rules representing the six basic behaviors controlling the platform's turning rate and speed (see [4] or [9]): GD → TR, GD → TS,OP → TS, "far" OP → TR, "near" OP → TR, "very near" OP → TR.

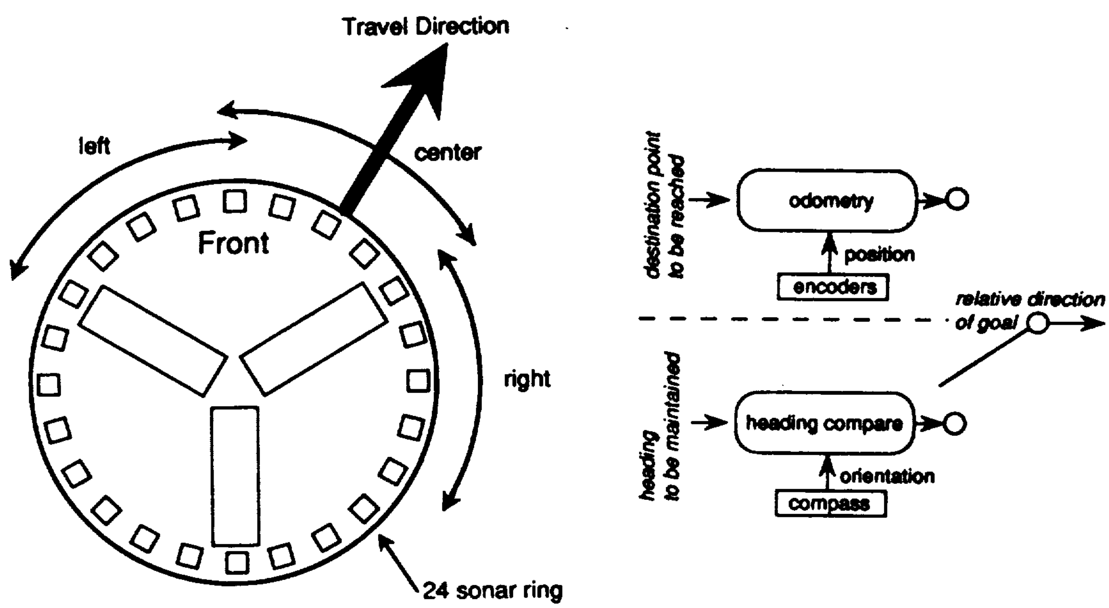

Fig. 1. Schematic of the three 5-sonar sectors providing obstacle proximity input data, and the two methods for calculating the goal direction depending on the mode of goal specification.

2.1 APPLICATION TO CAR DRIVING

One of the expected strengths of our proposed "Fuzzy-Behaviorist" approach using "human-like" behaviors is that the *linguistic logic* embodied in the behaviors should be invariant among systems of similar characteristics. In other words, for robots with similar perceptive and motion capabilities, the linguistic expression of given behaviors, and therefore their representation in the fuzzy framework, should be the same for compatible input and output. For example, a "goal tracking" behavior connecting the perceived goal direction to a rate of turn [e.g. IF (goal is to the right) THEN (apply increment of turn to the right)] should be invariant for any robot which has a means to perceive the goal direction and to perform the required turn. Using this property (and realizing that the rate of turn of a car is proportional to the steering angle of the wheels), all navigation behaviors developed for the laboratory omnidirectional platform appear directly applicable to the driving of a car of similar size, except for those behaviors which require a rate of turn too large for the car to perform because of its limited steering angle. The "very near" OP $\rightarrow$ TC behavior, which requires the platform to perform high rates of turn (using its omnidirectional capability) when obstacles are detected at dangerously close ("very near") distances, is the only behavior which therefore could not be considered invariant from the platform to the car.

As a demonstration of the transportability of invariant behaviors from one system to another, the same behaviors (except for the "very near" OP $\rightarrow$ TC behavior) and the very same fuzzy rules that were utilized for the omnidirectional platform were used to implement the autonomous control of a car on the basis of the same "three wide blurry eyes" and goal direction input. Figure 2 shows a simulation example of such a navigation in which the car has to reach a goal (in the upper right section) and then return to its start position (in the lower left section). Note that the out and return paths are different. Also note that a large maximum steering angle has been selected for the car in this simulation to allow very small radii of turn (e.g. see the sharp turn in the upper right section) and therefore prevent situations with "very near" obstacles.

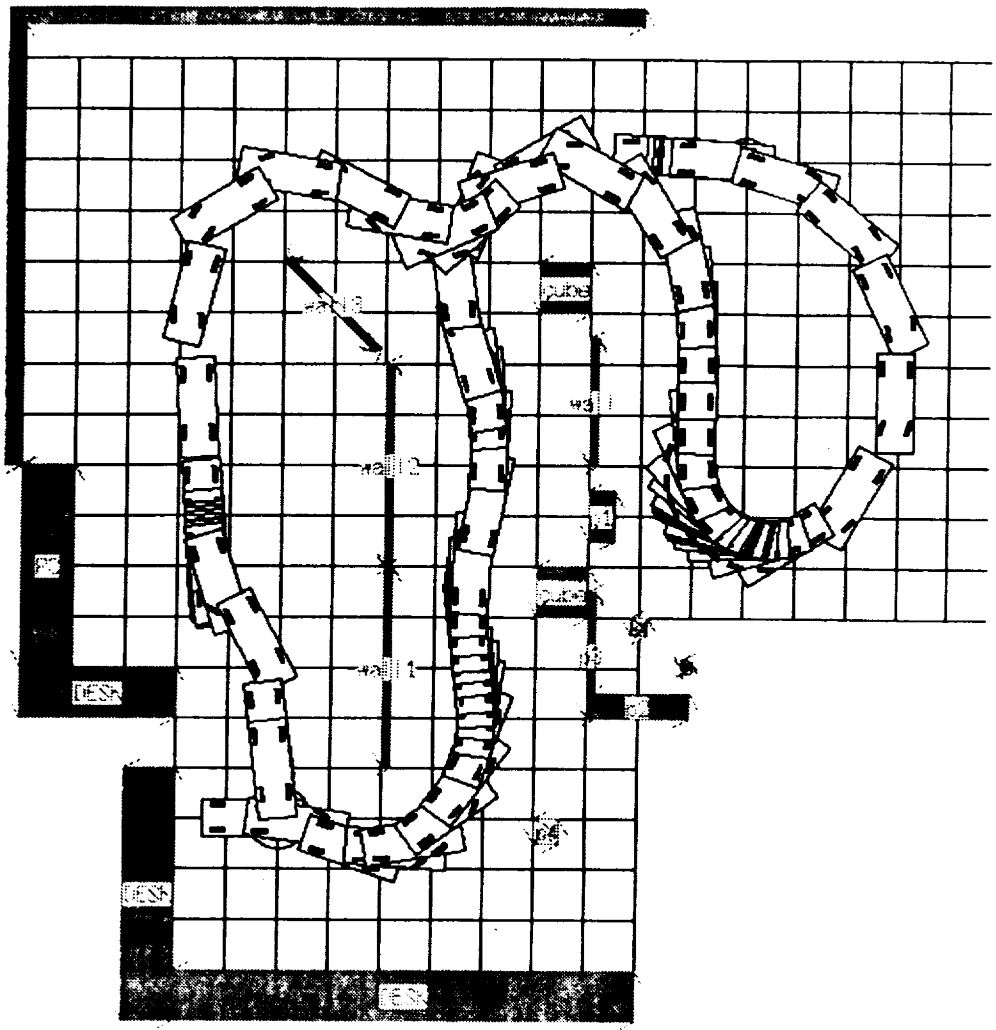

Fig. 2. Simulation example of the autonomous navigation of a car using three "wide" sonars and the same invariant navigation behaviors than for the omnidirectional platform.

2.2 ADDITION OF A MANEUVERING BEHAVIOR

To complete the navigation rule base for the driving of the car, a behavior has to be included to handle the situations where "very near" obstacles are detected. Another strength of our proposed "Fuzzy-Behaviorist" approach is its capability for superposition of elemental behaviors along a "subsumption-type" of architecture (e.g. see [11]), allowing for progressive addition of behaviors to the system to resolve situations of increasing complexity. Since the five other basic behaviors assure collision-free navigation amidst "far" and "near" frontal obstacles, the situations involving "very near" obstacles would occur when the car does not have enough space to complete a turn away from obstacles because of its limited steering angle and radius of turn, and thus would require some maneuvers using reverse gear. By observing human reactions to such stimuli, a "human-like" response was created which can be expressed as follows: IF (obstacle is "very near" on right (left)) THEN (steer right (left)) AND (back up). This response was further divided into a steer control behavior: "very near" OP $\rightarrow$ TR, and a speed control (back up) behavior: "very near" OP $\rightarrow$ TS, to respect our approach's requirement for independence of behaviors [4]. Note that this latter behavior is intrinsically "human-like" since it implements a human reaction which implicitly utilizes the inertia present in the car in order to produce the desired effect.

Figure 3 displays sample results showing several maneuvers generated by the two "very near" OP behaviors in a simulation of the autonomous navigation of a car using the three "wide sonar" eyes as a perception system. Note that in this simulation, the "front" of the car, where the three wide-sonar perception eyes are mounted, corresponds to the axle with non-steering wheels, while the axle with the steering wheels is to the "back" of the car. This was done to closely duplicate the configuration utilized in the outdoor experiments in which the perception system was positioned on the back trunk of the vehicle, as explained in the next section.

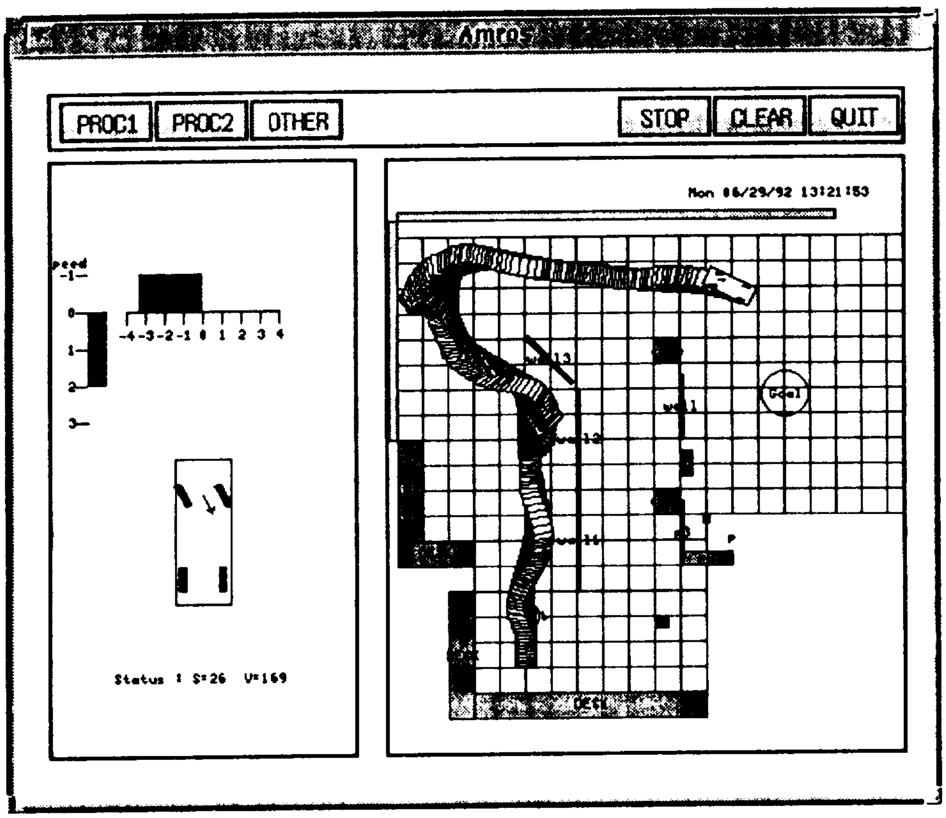

Fig. 3. Simulation example of the autonomous navigation of a car using three "wide" sonars and a maneuvering behavior to overcome the limited radius of turn.

2.3 ADDITION OF A DRIVER'S AID MODE

Once the development of the fuzzy rule base for autonomous navigation was completed and had been tested in various simulated environments, the system was investigated for use as a "driver's aid." In the simulation system, the output of the fuzzy inferencing was conveniently displayed on the screen, as is shown on the left-hand side of Fig. 3. The horizontal and vertical bar scales respectively represent the steering and speed commands which are calculated by the fuzzy inferencing and, in the autonomous navigation mode, are sent to the controls of the vehicle emulator. The schematic of the car below the bars shows the steering of the wheels implemented by the controller. Recall that the car moves "backwards" so that to perform a turn to the right, the wheels have to be steered to the left. In the driver's aid mode, the very same rule base, commands and displays are used to guide the operator in driving the car. In the simulations, the driver uses the keyboard arrow keys to add or subtract increments of speed or steering. In the implementation of the system on one of the company's cars, the driver conventionally uses the gas and brake pedals and the steering wheel to implement the commands.

For the testing and verification experiments, the driver was prohibited from seeing the environment while driving. This was done by covering the vehicle motion display part of the screen in the graphic simulations, and in the outdoor experiments by positioning the sensing platform on the rear trunk of the car and having the operator drive backwards while looking at the portable computer screen located on his/her lap. From this came the requirement for the "backwards" driving in the simulations and the corresponding reverse of the commands. Note that the commands are not displayed to the operator as crisp control values, but as bars of variable lengths over the generic speed and steering scales, effectively providing only the direction of the command (left or right, forward or back) and the *relative strength* (i.e., more steering, faster, slower, etc.) which the driver should apply on the controls between the maximum steering and speed values. It was interesting to observe each operator develop his/her own interpretation of and response to these relative commands, leading to quite different routes and maneuvering situations for the same start and goal positions. From the system's development point of view, this inclusion of the human in the control chain effectively consisted in including a source of unpredictable noise and delays in the actuation system. The successful operation of the rule base in this mode of driving provided a very stringent robustness test of the inferencing rule base.

3. OUTDOOR DRIVING EXPERIMENTS

Figure 4 shows the experimental set up for the outdoors experiments. The wheels of the omnidirectional platform which was used in previous laboratory experiments [9],[10], have been removed, and its upper plate supporting the sensors, batteries, and computers has been mounted on the trunk of one of the company's cars. Since the car was not equipped with wheel encoders, odometry could not be used and an electric compass provided the goal direction input with the navigation goal specified as a heading (e.g. North). To take into account the relative width of the real car with respect to that used in the simulations (of the same 2 foot width than the omnidirectional platform), the x axis of all membership functions involving distance were linearly scaled by a factor of three. The same input, rules, and behaviors developed in the simulation studies were used in these outdoor experiments. The output of the fuzzy inferencing was sent to a portable computer located in the cabin. The steering and speed commands were displayed on the computer screen using the same format than shown in Fig. 3 for the simulations. Since the car is not currently equipped with automated actuators on the steering column or the speed control system, these experiments were performed using the driver's aid mode of operation. The driver sat in a normal position in the car and was prohibited to look at the environment by having to constantly watch the commands on the computer screen located on the floor in the front compartment.

The type of environments in which the tests were preformed were the diversely occupied parking lots of ORNL, as can be seen in the background of Fig. 4. In this type of non-engineered environments, the car was very successfully driven in the "blind" driver's aid mode. Our future plans include the integration of encoders and servo controls on the wheels, steering, accelerator, and braking systems of the car to experiment with, test, and demonstrate the autonomous control mode in outdoors environment.

Fig. 4. Experimental set up during the outdoor experiments with driver's aid mode in one of the ORNL parking lots.

4. CONCLUSION

VLSI fuzzy inferencing chips and a "fuzzy behaviorist" approach have been used to demonstrate the feasibility of driving a car under sensor-based autonomous navigation or driver's aid mode using only sparse data from very inaccurate sensors. The "subsumption-type" formalism proposed for the development of fuzzy behavior-based systems has been found to allow easy development of the behaviors and progressive augmentation of the fuzzy rule base to deal with situations of increasing complexity, such as in the example treated here of a need for maneuvering due to the car's limited radius of turn. Additionally, the framework has been shown to allow the same behaviors, rules, and inferencing code to be used for systems with similar perceptive and kinematic characteristics, therefore greatly enhancing code transportability among robots and systems. As shown in the driver's aid feasibility study, the straightforward "linguistic" interfacing capability of the fuzzy behavior-based system is also of great appeal for telerobotics and man-machine decisional systems. Our ongoing activities are focusing on the use of a recently developed multi-chip fuzzy inferencing board, in conjunction with additional on-board image sensors, to increase the car's autonomous navigation capabilities with behaviors such as road following or highway driving, and correspondingly augment the safety enhancing driver's aid system for a variety of outdoor environments.

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