QUICK AND CLEAN: CONSTRAINT-BASED VISION FOR SITUATED ROBOTS

Alan K. Mackworth

Laboratory for Computational Intelligence
Department of Computer Science
University of British Columbia
Vancouver, B.C. V6T 1Z4, CANADA
E-mail: mack@cs.ubc.ca

ABSTRACT

Knowledge-based vision for robots needs a radically new approach. The traditional approach has not made substantial progress for various reasons including the engineering problems of building systems based on a hybrid on-line/off-line paradigm. A new situated agent approach is presented. The Constraint Net model of Zhang and Mackworth allows the designer to specify the robot's vision, control and motor systems uniformly as on-line systems. If the perceptual and control systems are designed as constraint-satisfying devices then the total robotic system, consisting of the robot symmetrically coupled to the environment, can be proven correct. Examples of this approach are given.

1. INTRODUCTION

Knowledge-based image interpretation needs to be re-interpreted. The traditional approach, based on the classic Good Old-Fashioned Artificial Intelligence and Robotics (GOFAIR) paradigm, proposes that domain-specific knowledge is used by the robot/agent at run-time to disambiguate the retinal array into a rich world representation. The argument is that the impoverishment and ambiguity of the visual stimulus array must be supplemented by additional knowledge. This approach has failed to make substantial progress for several reasons. One difficulty is the engineering problem of building robots by integrating off-line knowledge-based vision systems with on-line control-based motor systems. Especially in active vision systems [1] this integration is difficult, ugly and inefficient [2]. Because of such objections, some in the AI-robotics community have rejected the knowledge-based approach adopting instead an *ad hoc* Gibsonian situated approach to perception that exploits regularities of the particular environmental niche of the robot [3, 4, 5, 6]. In this paper, I argue that, with a radical re-interpretation of 'knowledge-based', we *can* design, build and verify quick and clean knowledge-based situated robot vision systems.

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2. ROBOT DESIGN METHODOLOGIES

We need practical and formal design methodologies for building integrated perceptual robots. A robot is, typically, a hybrid intelligent system, consisting of a controller coupled to its plant. The controller and the plant each consist of discrete-time, continuous-time or event-driven components operating over discrete or continuous domains. The controller has perceptual subsystems that can (partially) observe the state of the environment and the state of the plant.

Robot design methodologies are evolving dialectically [2]. The symbolic methods of GOFAIR constitute the original thesis. The antithesis is reactive Insect AI. The emerging synthesis, Sit-

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uated Agents, has promising characteristics, but needs formal rigor and practical tools. The critiques and rejection, by some, of the GOFAIR paradigm have given rise to the Situated Agent approaches of Rosenschein and Kaebling [7], Brooks [6], Ballard [1], Winograd and Flores [8], Lavignon and Shoham [9], Zhang and Mackworth [10, 2] and many others.

3. CONSTRAINT NETS

The Constraint Net (CN) model [11] is a formal and practical model for building hybrid intelligent systems as Situated Agents. In CN, a robotic system is modelled formally as a symmetrical coupling of a robot with its environment. Even though a robotic system is, typically, a hybrid dynamic system, its CN model is unitary. Most other robot design methodologies use hybrid models of hybrid systems, awkwardly combining off-line computational models of high-level perception, reasoning and planning with on-line models of low-level sensing and control.

CN is a model for robotic systems software implemented as modules with I/O ports. A module performs a transduction from its input traces to its output traces, subject to the principle of causality: an output value at any time can depend only on the input values before, or at, that time. The model has a formal semantics based on the least fixpoint of sets of equations [11]. In applying it to a robot operating in a given environment, one separately specifies the behaviour of the robot plant, the robot control program, and the environment. The total system can then be shown to have various properties, such as safety and liveness, based on provable properties of its subsystems. This approach allows one to specify and verify models of embedded control systems. Our goal is to develop it as a practical tool for building real, complex, sensor-based robots. It can be seen as a development of Brooks' subsumption architecture [6] that enhances its modular advantages while avoiding the limitations of the augmented finite state machine approach.

Although CN can carry out traditional symbolic computation on-line, such as solving Constraint Satisfaction Problems and path planning, notice that much of the symbolic reasoning and theorem-proving may be outside the agent, in the mind of the designer. GOFAIR does not make this distinction, assuming that such symbolic reasoning occurs explicitly in, and only in, the mind of the agent.

In CN the modelling language and the specification language are totally distinct since they have very different requirements. The modelling language is a generalized dynamical system language. Two versions of the specification language, Timed Linear Temporal Logic [12] and Timed $\forall$-automata [13], have been developed with appropriate theorem-proving and model-checking techniques for verifying systems.

4. CONSTRAINT-BASED CONTROLLERS

Many robots can be designed as on-line constraint-satisfying devices [13, 14, 12]. A robot in this restricted scheme can be verified more easily. Moreover, given a constraint-based specification and a model of the plant and the environment, automatic synthesis of a correct constraint-satisfying controller becomes feasible, as shown for a simple ball-chasing robot in [12].

A constraint is simply a relation on the phase space of the robotic system, which is the product of the controller, plant and environment spaces. A controller is constraint-satisfying if it, repeatedly, eventually drives the system into an ϵ-neighborhood of the constraint using a constraint satisfaction method such as gradient descent.

Theory is vacuous without an appropriate application to drive designs, experiments and implementations. The ideas developed in this paper are illustrated by application to the challenge of designing, building and verifying active perception systems for robot soccer players with both off-board and on-board vision systems.

5. THE DYNAMO ROBOTS

In the Dynamo (Dynamics and Mobile Robots) Project in our laboratory, we are experimenting with multiple mobile robots under visual control. The Dynamite testbed consists of a fleet of radio-controlled vehicles that receive commands from a remote computer. Using our custom hardware and a distributed MIMD environment, vision programs are able to monitor the position and orientation of each robot at 60 Hz; planning and control programs generate and send motor commands at the same rate. This approach allows umbilical-free behaviour and very rapid, lightweight fully autonomous robots. Using this testbed we have demonstrated various robot tasks [15], including playing soccer [16].

One of the Dynamo robots, Spinoza, is a self-contained robot consisting of an RWI base with an RGB camera on a pan-tilt platform mounted on top and binocular monochrome stereo cameras in the body. As a illustration of these ideas consider the task for Spinoza of finding, tracking and chasing a soccer ball, using the pan-tilt camera. After locating the moving ball Spinoza is required to move to within striking distance of the ball and maintain that distance. The available motor commands control the orientation of the base, the forward movement of the base, and the pan and tilt angles of the camera. The parameters can be controlled in various relative/absolute position modes or rate mode. The available rate of pan substantially exceeds the rate of body rotation. A hierarchical constraint-based active-vision controller can be specified for Spinoza that will achieve and maintain the desired goal subject to safety conditions such as staying inside the soccer field, avoiding obstacles and not accelerating too quickly. If the dynamics of Spinoza and the ball are adequately modelled by the designer then this constraint-based vision system will be guaranteed to achieve its specification.

6. CONCLUSIONS

This paper describes the motivation, some results and some current directions of a long-term project intended to develop a new approach to the specification, design and implementation of robotic systems. Robots are just a typical class of hybrid systems. One of the most important challenges facing us is to develop unitary theoretical and practical tools for designing hybrid embedded intelligent systems. Our approach to this challenge also leads to a new technical paradigm for the traditional notion of 'knowledge-based' vision systems.

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