Towards the Unification of Navigational Planning and Reactive Control

Ronald C. Arkin

School of Information and Computer Science
Georgia Institute of Technology
Atlanta, GA 30332

Working Notes of the AAAI Spring Symposium on Robot Navigation
Stanford University, March 28-20, 1989

Abstract

The illusion that reactive and hierarchical planning methods are at odds with each other needs to be dropped. By exploiting each method's strengths, a synthesis of hierarchical and reactive paradigms can yield robust, flexible, and generalizable navigation. Psychological and neuroscientific studies support this claim.

1. Introduction

The integration of knowledge-based navigational path planning and reactive navigation requires the confrontation of many difficult problems. It can be seen that each of these methods addresses different subsets of the complexities inherent in intelligent navigation. It is our contention that neither navigational approach is entirely satisfactory when taken in isolation, but rather that both must be taken into account for the production of an intelligent, robust, and flexible system.

Navigational path planning without consideration for the difficult issues of plan execution leads to restricted usage in very narrow problem domains and/or extremely brittle mobile robot systems. A robot must have the ability to respond rapidly and effectively to changes that occur within its world. If a system attempts to model and preplan for all of the eventualities that could occur, it could get so bogged down that the planning process never terminates (the qualification problem). On the other hand, it is unsafe for a robot to make gross assumptions about the world that do not reflect its dynamic nature.

When most reactive/reflexive navigational systems are considered by themselves, it can be seen that robustness is gained at the expense of some very important navigational characteristics: flexibility and adaptability. Reactive navigation can be viewed as a restrictive form of navigation that is quite well-suited for specific fixed tasks and behaviors but lacks the necessary adaptability to provide truly general and versatile machines. The issues of action and perception are addressed, but cognition is ignored, limiting these robots to mimicking low-level life forms. Representational knowledge **is** necessary to enhance and extend the behaviors of these machines into more meaningful problem domains. This includes the incorporation of memory and dynamic representations of the environment.

We feel that success ultimately lies in the integration of both of these techniques. Dynamic replanning must be affected not only in a reactive manner but also in the context of a more abstract plan, one representing the goals and intents of the robot at a variety of planning levels. The issue should not be reactive **versus** preplanned control, but rather how to synthesize a control regime that incorporates both of these methodologies. Our research in intelligent navigation is addressing this directly.

2. The Illusion

Two opposing camps have manifested themselves in the navigational research community: the hierarchical school and the reactive school. Strong cases can and have been made for the superiority of each of these methods. We take the position that neither camp is superior by itself, but rather that an alliance should be forged between them. This is a consequence of the fact that each approach is attacking a fundamentally different part of the problem.

The hierarchical approach is best suited for the integration of world knowledge and user intent to arrive at a navigational plan *prior* to its execution. Replanning with this method, however, at levels where sensory data is merged into world models is cumbersome. The reactive approach, on the other hand, is well-situated to deal with the immediacy of sensory data, but ill-equipped to integrate world knowledge. A clear-cut distinction can be seen in the hierarchical planner's heavy reliance on world models (either *a priori* or dynamically acquired) while most reactive planning systems avoid the use of world representations almost entirely.

The illusion is that both of these methods are dealing with the same problem. The reality is that the hierarchical school is involved with plan formulation while the reactive approach copes with plan execution and the issues of dynamic replanning.

2.1 A Brief History

Representative examples of both hierarchical and reactive planners appear below, along with an assessment of the successes and weaknesses of each paradigm.

2.1.1 The Hierarchical School

The many examples of hierarchical control systems share a structured and clearly identifiable subdivision of functionality. This functionality is relegated to distinct program modules which communicate with each other in a predictable and predetermined manner. Numerous examples illustrate this technique [3,14,15,17,20,22].

A typical subdivision of functionality is dependent on both planning scope and temporal constraints. At the highest level of a hierarchical planner, the most global and least specific plan is formulated. The time requirements for the production of this plan are the least stringent. As one proceeds down the planning hierarchy, the scope becomes narrower, focusing on smaller regions of the world while requiring more rapid solutions. At the lowest levels, rapid real-time response is required, but the planner is only concerned with its immediate surroundings and has lost sight of the "big picture". Meystel [18] has developed a theory for hierarchical planning which emphasizes the significance of scope and invokes the concept of nested controllers.

2.1.2 The Reactive School

Brooks' subsumption architecture is perhaps the first and best known representative of the reactive school of navigational planning. This approach advocates the "horizontal decomposition" of planning into a collection of concurrent layered behaviors, each connected to its own sensory inputs. Although this method has arguably provided the most successful demonstrations of autonomous behavior to date, it is lacking in its ability to incorporate world knowledge and alterations in user intent based upon changes in environmental circumstances and internal conditions. Even though early models of the subsumption architecture [10] did provide for the integration of world models, it is our position that a better approach involves a synthesis of hierarchical planning and reactive control.

Several other navigational systems using reactive planning have been developed. These include Payton's reflexive behaviors [21], Kadonoff's arbitration strategies [13], and Arkin's motor schemas [5]. Although each of these methods differ significantly in the way the primitive behaviors are integrated, controlled, and selected, they share in common a decomposition of motor action into a collection of primitives which can be closely tied to incoming sensory information.

2.2 Removal of the Veil

What can we extract from this quick review? We have seen that hierarchical planners have a heavy reliance on world models; they can readily integrate world knowledge, and navigational planning in the context of scope can be readily handled with this technique. These features are crucial characteristics for plan formulation. Reactive planners produce robust, demonstrable navigational successes, they afford modular development and incremental growth and are tightly coupled with arriving sensory data. These are crucial characteristics for plan execution.

A union of these two approaches can potentially yield the best of both worlds. If done poorly it can yield the worst of both worlds. How can a unifying methodology be developed that will ensure a system that is capable of robust navigational plan execution yet taking into account a high-level understanding of the nature of the world and a model of user intent? (Read on ...)

3. The Path to Unification

Recognizing that two different problems are being addressed, we look not towards the superiority of one navigational methodology over the other, but rather towards a synthetic, integrative approach that applies both of these paradigms to the issues of navigational planning, using each where it is most appropriate. We do this by first examining how the most successful systems for navigation, animals, provide psychological and neuroscientific evidence for the co-existence of two compatible planning and execution systems: one concerned with plan formulation, and the other with automatic reflexive plan execution.

3.1 Motivation

Before studying the biological basis for our position, we examine another class of methods involved in finding solutions to navigational problems which we collectively refer to as "transcendental" engineering. These researchers remain unconcerned with the existing solutions found in biological systems and believe that they should not be constrained by or concerned with such methods. A representative transcendental engineering example is found in the work involving high-speed dynamic control for automatic road-following proceeding in Dickmann's group at Munich [11]. Although arguments against relying on biological systems for potential solutions can be made (e.g., robots use fundamentally different hardware, evolution is perhaps not the best instructor) we nonetheless are convinced that much insight can be gained by an understanding of the machinations of biological systems.

Psychological and neuroscientific models of behavior can provide an existence proof for the success of the integrative strategy that we have proposed for the combination of elements of hierarchical and reactive planning and control. It is also important to be flexible in our use of the models developed by scientists in other fields, as our goal is not to create artificial duplicates of existing creatures, but instead functioning autonomous agents that may have some behavioral overlap with their biological counterparts.

3.1.1 Psychological evidence

Psychological studies [24] have indicated the existence of two distinct modes of behavior: willed (controlled) and automatic. Norman and Shallice [19] have enumerated the characteristics of tasks requiring willed control (deliberate attentional resources):

- Planning (decision-making)
- Troubleshooting
- Novel or poorly learned actions (non-reflexive)
- Dangerous or difficult actions
- Overcoming habit or temptation

Other motor actions are typically automatic (reactive) and can occur without attention. A contention scheduling mechanism for multiple active motor schemas models the production of co-ordinated behavior. Higher level processes involving attention, alter the threshold values for schemas (loosely translated as basic behaviors), dynamically changing the interplay between them. (Psychological support for schema use in a strictly horizontal manner is well-established [23]). This model incorporates aspects of both vertical and horizontal control threads (in a similar sense as Brooks' use [10]). Multiple horizontal behaviors are mediated by vertical threads which interconnect the various behaviors and allow for their dynamic modulation as a result of attentional resources (planning, troubleshooting, etc.). The schemas are triggered by perceptual events but modulated by attentional processes. This provides a coherent psychological model for the integration of multiple concurrent behaviors that are controlled by higher level processing.

The Norman-Shallice model points out several interconnects between deliberate and automatic control:

- Automatic schemas are modulated by attention arising from deliberate control.
- Schema selection is the principal function of deliberate control. (Vertical threads provide the selection mechanism).
- Schemas (behavioral tasks) are in competition with each other.
- Neuropsychological experiments are consistent with this model.

The evidence supporting the existence of a distinct supervisory attentional system is considerable. Even if this theory ultimately fails as an account of the basis for psychological motor behavior and planning, the model may nonetheless prove useful in its own right as a basis for the integration of hierarchical and reactive control systems in robots.

3.1.2 Neuroscientific evidence

Higher level control of multiple independent subsystems is well evidenced in the neuroscientific literature. There are several instances where the coordination of locomotion is determined by autorhythmic neurons that are used for motor action pattern making (e.g., in the beating of fins in fish). Motor neurons, whose firing is invoked from higher level neural processing, activate these automatic behavioral patterns [12].

Experimental studies by Humphrey [16] at Emory University have elucidated the interconnection between low-level local motor control and its modulation by higher level processing. By analyzing the signals arising from the central nervous system, spinal neural circuits, and the local innervation of muscles in the context of grasping in monkeys, several distinct roles for control were observed. Local control in essence managed the servoing processes while higher level processing providing the signals to adapt to large changes in position.

4. AuRA as an Integrative Method for Planning/Execution

The Autonomous Robot Architecture (AuRA [1,2]) has from its onset been concerned with the integration of hierarchical and reactive planning mechanisms. AuRA is the framework in which our experiments in mobile robot navigation are conducted. Within the context of this system, we have developed techniques for navigational path planning in the presence of *a priori* world models [3], spatial uncertainty management [4], reactive/reflexive navigation [5], dynamic replanning in hazardous environments [6], and the integration of vision in the context of action-oriented and expectation-based perception [7]. Navigational experiments using our mobile robot have been conducted in several locales, including the interior of buildings, outdoor campus settings, and manufacturing environments [8].

Our system exploits several forms of knowledge representation: *a priori* world maps and landmark models, dynamically acquired spatial occupancy maps in a local context, and collections of intelligent motor behaviors and perceptual strategies (schemas) which are selected, parameterized, and instantiated in a manner consistent with available knowledge.

Much of our work has been and continues to be influenced by psychological and neuroscientific studies [9]. Although complete integration of the hierarchical planner (consisting of a mission planner, navigator and pilot) remains to be accomplished, the mechanisms for behavior selection and modulation are in place. The mission planner is concerned with the high-level broad-brush concerns of the robot's mission. It has the grandest scope and the least temporal constraints. The subordinate navigator chooses a point-to-point path consisting of a series of piecewise linear segments produced through an *a priori* map of the robot's world and that is consistent with the mission planner's specifications. The pilot then focuses further on an individual segment of the navigator's path and selecting and parameterizing the appropriate motor schemas and perceptual strategies necessary for successful completion of the path leg.

When plan formulation is completed by the selection of motor and perceptual schemas, plan execution is turned over to the motor schema manager which instantiates the individual schemas. The configuration and activity levels for each of these individual reactive schemas changes dynamically as the robot proceeds through its world.

If goal attainment is not realizable at the reactive plan execution level, the hierarchical planner is reinvoked to compute an alternate strategy based upon available world models (first referring to a dynamically acquired model and if that fails then the *a priori* one). Complete integration of the plan formulation/execution system and coping with plan failure constitute two of our active research areas.

5. Conclusions

The false dichotomy that exists between hierarchical and reactive planning systems should be dropped. Strong evidence exists that forms of both of these systems are used in animal navigation. From this, the inference can be drawn that they are compatible and symbiotic. Plan execution is highly appropriate for reactive control, while plan formulation is appropriate for hierarchical systems which maintain the ability to reason over levels of world representation.

Our research will continue in the hopes of discovering the true synergism that can exist between these superficially different paradigms. Integration of new models of behavior (e.g., the Norman-Shallice model (Sec. 3.1.2 [19])) can provide a firm foundation to build upon.

REFERENCES

[1] Arkin, R.C., Riseman, E. and Hanson, A., 1987. "AuRA: An Architecture for Vision-based Robot Navigation", *Proceedings of the 1987 DARPA Image Understanding Workshop*, Los Angeles, CA, pp. 417-431.

[2] Arkin, R., "Towards Cosmopolitan Robots: Intelligent Navigation of a Mobile Robot in Extended Man-made Environments", *Ph.D. Dissertation*, *Technical Report 87-80*, Department of Computer and Information Science, University of Massachusetts, 1987.

[3] Arkin, R., "Navigational Path Planning for a Vision-based Mobile Robot", To appear in *Robotica*, 1988.

[4] Arkin, R., "Spatial Uncertainty Management for a Mobile Robot and its Role in Expectation-Based Perception", to appear in *Proc. of Symposium on Robot Control '88 (Syroco)*, Karlsruhe, W. Germany, Oct. 1988.

[5] Arkin, R., 1987. "Motor Schema Based Navigation for a Mobile Robot: An Approach to Programming by Behavior", *Proceedings of the 1987 IEEE Conference on Robotics and Automation*, Raleigh, NC, pp. 264-271.

[6] Arkin, R., 1988. "Homeostatic Control for a Mobile Robot: Dynamic Replanning in Hazardous Environments", to appear in the *Proceedings of the SPIE Conference on Mobile Robots III*, Cambridge Symp. on Advances in Intelligent Robotics Systems.

[7] Arkin, R., Riseman, E. and Hanson, A., 1987. "Visual Strategies for Mobile Robot Navigation", *Proceedings of the IEEE Computer Society Workshop on Computer Vision*, Miami Beach, Florida, pp. 176-181.

[8] Arkin, R., "Intelligent Mobile Robots in the Workplace: Leaving the Guide Behind", *Proceedings of The First International Conference on Industrial and Engineering Applications of Artificial Intelligence and Expert Systems*, pp. 553-561, 1988.

[9] Arkin, R., "Neuroscience in motion: The Application of Schema Theory to Mobile Robotics", chapter to appear in *Visuomotor Coordination: Amphibians, Comparisons, Models, and Robots*, eds. J.-P. Ewert and M. Arbib. New York: Plenum Press, 1989.

[10] Brooks, R., "A Robust Layered Control System for a Mobile Robot", *IEEE Jour. of Robotics and Auto.*, Vol. RA-2, No. 1, pp. 14-23, 1986.

[11] Dickmanns, E. and Zapp, A., "Guiding Land Vehicles along Roadways by Computer Vision", *AFCET Conference*, Toulouse, France, 1985.

[12] Ewert, J.O., *Neuroethology*, Springer-Verlag, 1980.

[13] Kadonoff, M., Benayad-Cherif, F., Franklin, A., Maddox, J., Muller, L., Sert, B. and Moravec, H., "Arbitration of Multiple Control Strategies for Mobile Robots", Mobile Robots - *SPIE proc. Vol. 727*, 1986.

[14] Keirsey, D., Mitchell, J., Payton, D., and Preyss, E., "Multilevel Path Planning for Autonomous Vehicles", *SPIE Vol. 485, Applications of Artificial Intelligence*, pp. 133-137, 1984.

[15] Koch, E., Yeh, C., Hillel, G., Meystel, A., and Isik, C., "Simulation of Path Planning for a System with Vision and Map Updating", *Proc. IEEE Int. Conf. Robotics and Automation*, St. Louis, Mo., pp.146-160, 1985.

[16] Humphrey, D., Personal Communication.

[17] Meystel, A., "Planning in a Hierarchical Nested Autonomous Control System", *Mobile Robots - SPIE Proc. Vol. 727*, pp. 42-76, 1986.

[18] Meystel, A., "Theoretical Foundations of Decision Making Processes for Design and Control of Intelligent Mobile Autonomous Robots", Technical Report, Drexel University, 1986.

[19] Norman, D. and Shallice, T., "Attention to Action: Willed and Automatic Control of Behavior", from *Consciousness and Self-regulation: Advances in Research and Theory*, eds. Davidson et al, Vol. 4, Plenum, pp. 1-18, 1986.

[20] Ooka, A., Ogi, K., Wada, Y., Kida, Y., Takemoto, A., Okamoto, K., and Yoshida, K., "Intelligent Robot System II", *Robotics Research, Second Int. Symposium*, ed. Hanafusa and Inoue, MIT Press, pp. 341-347, 1985.

[21] Payton, D., "An Architecture for Reflexive Autonomous Vehicle Control", *IEEE Conf. on Robotics and Auto.*, pp. 1838-1845, 1986.

[22] Pearson, G. and Kuan, D., "Mission Planning System for an Autonomous Vehicle", *IEEE Second Conf. On Artif. Intel. App.*, pp. 162-167, December 1985.

[23] Schmidt, R., "A Schema Theory of Discrete Motor Skill Learning", *Psychological Review*, 82, pp. 225-260, 1975.

[24] Shiffrin, R. and Schneider, W., "Controlled and Automatic Human Information Processing: II. *Psychological Review*, 84, pp. 127-190, 1977.