Review

A review of control architectures for autonomous navigation of mobile robots

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A mobile robot as an intelligent system needs to sense the surroundings, perceive the working environment, plan a trajectory and execute proper reaction using the information. Robotic control architectures define how these abilities should be integrated to construct and develop an autonomous navigation. The control architectures could be classified into three categories: Deliberative (Centralized) navigation, Reactive (Behaviour-based) navigation and hybrid (Deliberative - Reactive) navigation. This paper reviews various control architectures for autonomous navigation of mobile robots. The significance, advantages and drawbacks of the architectures are discussed and compared with each other.

Key words: Intelligent system, mobile robot, autonomous navigation, control architecture.

INTRODUCTION

Since early 1960's, researches on mobile robot navigation have been gradually increased. Different applications for mobile robots represent different navigation problem. It is essential for intelligent mobile robots to sense and perceive the working environment, plan a path, make a decision and execute appropriate reaction using the information (Vuković and Miljković, 2009). Control architectures define how these abilities should be integrated to get desired results. Therefore, various control architectures have been proposed to design and develop of robust, flexible, reliable and high-performance control systems for autonomous navigation of mobile robot. Each of the control architectures implies new concepts and solutions to deal with the navigation problem. The control architectures could be classified into three categories: Deliberative (Centralized) navigation, Reactive (Behaviour-based) navigation and hybrid (Deliberative - Reactive) navigation. The deliberative (Centralized) navigation architecture (Chatila and Laumond, 1985; Giralt et al., 1984; Laird and Rosenbloom, 1990; Moravec and Cho, 1989; Thorpe,

1993; Jochem et al., 1995) creates a global model of working environment through sensory system or user input.

Deliberative planning searches for the optimal path and generates a plan to reach the goal. Then the execution system is applied to perform an action within the context of the static model of environment and planning system to accomplish a given task (Huq et al., 2008). The reactive (Behaviour-based) architectures (Ye and Wang, 2000; Kasper et al., 2001; Seraji and Howard, 2002; Yang et al., 2006; Motlagh et al., 2008) were developed from 1980's to deal with shortcomings of the deliberative approaches in dynamic and unknown environments. These architectures generate control commands based on currently perceived environment. Therefore, it is not necessary to build a complete model of environment and the sensed data directly couples to the robot's actuators using a particular set of transfer functions called task-achieving modules or behaviours.

Hybrid control architecture first was developed by Arkin (1989, 1998) and Murphy (2000) which involves the advantages of planning in deliberative architectures and quick response of reactive architectures in dynamic or unknown environment. Then, the hybrid control architectures (Weitzenfeld and Arkin, 1998; Averbukh,

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1999; Billard and Hayes, 1999; Yoichiro and Arkin, 2003;Minguez and Montano, 2005; Du et al., 2007; Vuković and Miljković, 2009) were developed in the last few years to presents new approaches to get supervisory control systems that utilize reactive and deliberative control architectures.

In this paper a short review and analysis of the proposed control architectures for autonomous navigation of mobile robot is presented. The significance, advantages, disadvantages and effectiveness of the architectures are compared with each other.

Deliberative control architecture

The Deliberative (Centralized) navigation architecture is the oldest schema in artificial intelligence (AI). The deliberative techniques (Schwartz and Sharir, 1983; Nagatani et al., 1998; Canny, 1987; Mitchell, 1986; Takahashi, 1989; Latombe, 1991; Pruski and Rohmer, 1997) use a global world model provided by user input or sensory information to generate appropriate actions for the mobile robot to reach the target. As shown in Figure 1, the deliberative control architecture comprises three modules: sensing, planning and action modules. First robot sense it's surrounding and creates a world model of static environment by combining sensory information. Then it employs planning module to search an optimal path toward the goal and generate a plan for robot to follow.

Finally, robot executes the desired actions to reach the target. After a successful action, robot stops and updates information to perform the next motion. Then, it repeats the process until it reaches the goal (Huq et al., 2008; Yang et al., 2006). Top-down approach in planning module is an important characteristic of this architecture where high level constraints are broken into low level commands. It can coordinate multiple goals and constraints within a complex environment (Huq, 2008). However, in deliberative navigation, accurate model of environment is needed to plan a globally feasible path. It is difficult to obtain a completely known map. To perform necessary calculations, enormous processing capabilities and memory is needed. Moreover, the top-down approach of planning produces delay in navigation process and if any modules do not function properly, the system may fail entirely.

Therefore, these approaches are not proper in the presence of uncertainty in dynamic or real world.

Reactive control architecture

Reactive (behaviour-based) navigation architecture was developed by Brooks (1986) to tackle the deliberative navigation problems in dynamic and unknown environments. These approaches generate control commands based on current sensory information. To
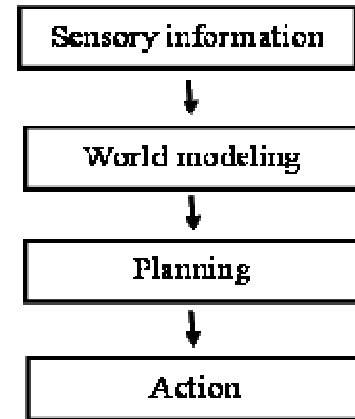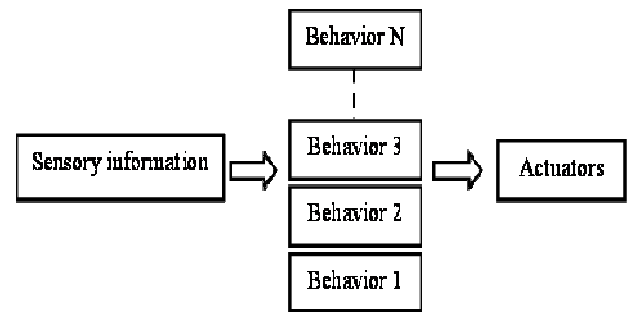
Figure 1. Deliberative architecture.

Figure 2. Behavior- based overall architecture.

take actions, the robot uses the local model of environment without planning process. Therefore, it is not necessary to build a complete model of environment. Bottom-up approach for decision making is used in the behaviour based architectures in which high level constraints are not integrated in action generation process.

Reactive navigation has a quick response in the dynamic and unknown environment. Figure 2 represents the overall architecture of behaviour-based approaches. In first layer, robot gathers sensory information. Then a transfer function called behaviour receives particular sensory inputs perception and transforms them into the predefined response. Finally, the robot executes an action based on the output of active behaviour. In fact, complex navigation tasks are broken down into several simpler and smaller sub-level tasks which improve the total performance of the navigation system. Two basic behavior-based control architectures include subsumption architecture (Brooks, 1986) and motor schemas (Arkin, 1989). Subsumption control architecture was introduced by brooks (1986) at Massachusetts Institute of Technology (MIT).

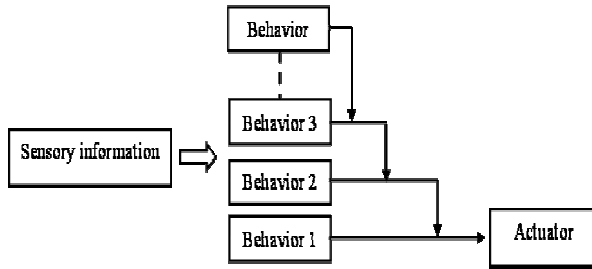The subsumption behavior-based control system is

Figure 3. Subsumption architecture.

Figure 4. Motor schema architecture.

composed of several layers of task-achieving behaviors where each behavior can receive sensory information for a given task (obstacle avoidance, wall following, target seeking, etc.). The task achieving process increases responsiveness and reduces planning complexity of the control system to a dynamic and unknown environment. In subsumption architecture, the planning module is eliminated from the control architecture and the focus is exclusively on the sensing and acting modules. Unlike the deliberative approaches, the behaviors provide a direct coupling between sensory inputs and robot's actions. As Figure 3 shows, in subsumption architecture, behaviors are layered and each behavior receives particular sensory information.

Coordination of behavior layers refers to the priority-based arbitration. Priority-based arbitration is a process of deciding which behavior to be active when multiple conflicting behaviors are trigged (Dupre, 2007). Therefore, the highest active behavioral module generates the overall output of architecture. Another behavior-based architecture proposed by Arkin (1998) is motor schemas architecture (Figure 4) which was motivated by biological sciences based on perceptual schemas. The motor schemas theory explains the motor behavior in terms of the simultaneous control of many different activities. Each behavior can produce an output in the vector form. These outputs are combined and then the overall response of the system is achieved by the vector summation. For example, a potential field can be defined as the output of each schema. The commanded movement is a vector which is the superposition of all fields.

Subsumption architecture advocates the competitive selection of behaviours, while the motor schemas rely on the use of cooperative coordination. Motor schema provides an ability to simultaneously use the outputs of more than one behavior with capturing their particular influence on overall output (Vuković and Miljković, 2009). The overall advantages of behaviour-based navigation systems are:

i) Their ability to build a navigation system in an incremental way of layer upon layer.
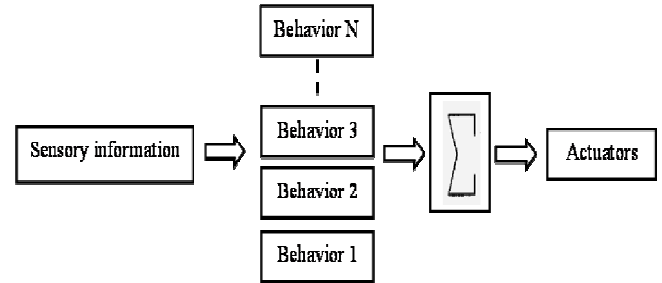
ii) Their quick reaction to the unknown and dynamic environment.
iii) They do not require modelling and storing the whole model of the environment.
iv) There is less computation and shorter delay between perception and action.
v) And they are more robust and reliable which means in case of a behaviour unit failure, the other units continue the tasks.

The drawbacks of behaviour-based control are as follows:

i) Difficulty in coordination among the behaviours, the interaction between the system and environment is difficult and less predictable.
ii) Behaviours are low level so they do not reflect high level tasks.
iii) Lack of planning module could be not appropriate for some complicated tasks.

Hybrid control architecture

Although reactive navigation architectures established a successful framework for mobile robot navigation, there are still some problems in regards with the complex unknown environment. To perform an autonomously navigation in a real world some features of deliberative architecture combines with the reactive architecture which called hybrid architecture. The hybrid control architecture could be classified to three styles (Murphy, 2000): Managerial style, state hierarchies and model-oriented. In Managerial Style (Yavuz and Bradshaw, 2002; Arkin, 1987; Busquets et al., 2003; Kolp et al., 2006; Kim and Chung, 2006), the deliberative module is in charge of planning in higher level. Then, the plans are sent to low level which is reactive module to be implemented. Each module attempts to modify the problems and solve them itself or refines by superior module if cannot solve its own problem.

The State-hierarchies (Bonasso et al., 1997; Lindstrom, 2000) use the knowledge of robot's state in past, present
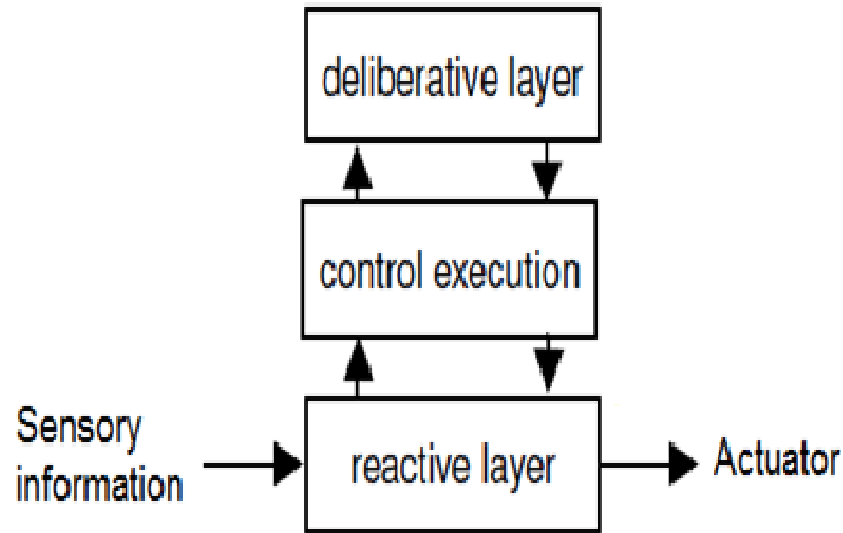
Figure 5. Hybrid control architecture (Perez, 2003).

Table 1. Analysis of the control systems architecture.

Architecture Specification	Deliberative	Reactive	Hybrid
Goal oriented	Very good	Not good	Good
Flexibility	Very bad	Very good	Very good
Ease of application	Very bad	Very good	Good
Reactivity	Very bad	Very good	Good
Optimal operation	Very good	Very bad	Good
Task learning	Very good	Moderate	Moderate
Robustness	Not good	Good	Very good
Planning	Very good	Not good	Good
Efficiency	Not good	Very good	Very good

and future. The deliberative layer requires the robot's past state (what the robot has done) to predict the future (path planning). The reactive layer functions in the present state (self- awareness) to complete deliberative planning instruction and generate the robot's motion. A model-oriented style (Konolige, 1997) more concentrates on global model of environment and it is similar to the deliberative architecture. However, the updated global model of environment is used by reactive layer immediately to reduce deliberative processing time (Davies, 2007).

The common hybrid control architectures consist of three layers: deliberative layer, control execution layer and reactive (behavior-based) layer (Figure 5). The deliberative navigation is applied for high level issues to develop an optimal plan. The high level constraints consist of sensor fusion, map building and planning. Then, the optimum commands from the higher level are sent to the reactive layer to generate the robot's action. The execution layer (behaviour-coordinator) is responsible to supervise the interaction between the high level layer and low level layer (Perez, 2003). The integration of various features in the hybrid architecture form a novel flexible and robust architecture for control systems.

The hybrid control architecture specifications in comparison with the deliberative and reactive architectures are summarised in Table 1. Next, each specification is described in Table 2.

Conclusion

Various control architectures for autonomous navigation of mobile robot have been described and compared in this paper. Among the proposed architectures, the

Table 2. Description of the specifications used in the evaluation of the control architectures.

Specification	Description
Goal oriented	Capability of the control system to provide means to accomplish multiple goals
Flexibility	Ability of adding new sub-systems or making any modifications and additions to a system functions without disrupting the established functionality (Yavuz and Bradshaw, 2002)
Ease of application	Refers to ease of an architecture to be understood, developed, tested and debugged
Reactivity	Ability of a system to respond and adapt to the sudden changes in the environment
Optimal operation	Capability of a system to obtain optimal cost function in motion criteria such as distance, time, oscillation, etc.
Task learning	Ability of the system to learn through a teach mode or operation to carry out specific tasks
Robustness	Capability of a system to handle sudden changes, imperfect inputs, and unexpected malfunctions
Planning	A set of partially ordered tasks for the robot to perform and work on a problem at the highest level of abstraction possible so as to make its problem space as small as possible until a plan is finished
Efficiency	Contains the capabilities and performance of a system to maximize individual utility and cooperation of subtasks to generate an optimized and smooth trajectory

deliberative architecture was more promising in high level control to obtain optimal path toward the target. However, it fails in dynamic or unknown environments. The reactive architectures had a better performance dealing with uncertainties for fast obstacle avoidance of the robot in unknown or dynamic environment but still have some difficulties dealing with complicated tasks.

To achieve a comprehensive navigation, robot needs more abilities that exceeds deliberative and reactive paradigms such as perception and world representation ability to enable information gathering and processing, fast reacting for static or dynamic obstacle avoidance, map building ability to insure the robot to be able to localize itself relative to the environment, inference and decision making ability to make reliable decisions based on that particular information. Therefore, the deliberative and reactive architectures have been combined and formed hybrid control architecture in the way to cope with the navigation problems. The review of the various control architectures showed that the hybrid scheme has the best performing supervisory control architecture and it is more prosperous and promising dealing with unknown, dynamic navigation problem.

REFERENCES

Arkin RC (1987). Towards Cosmopolitan Robots: Intelligent Navigation in Extended Man Made Environments. Phd Thesis, COINS Technical Report 87-80, Department of Computer and Information Science, University of Massachusetts.

Arkin RC (1989). Motor schema-based mobile robot navigation. Int. J. Robot Autom., 8(4): 92-112.

Arkin RC (1998). Behavior- Based robotics The MIT press, Cambridge, MA.

Averbukh AB (1999). Hybrid intelligent architecture for real time processing. IEEE Int. Joint Conf. Neural Network, pp. 4107-4110.

Billard A, Hayes G (1999). DRAMA - A Connectionist Architecture for Control and Learning in Autonomous Robots. Int. Soc. Adaptive Behav., 7: 35-63.

Bonasso RP, Firby RJ, Gat E, Kortenkamp D, Miller D, Slack M. (1997). Experiences with an architecture for intelligent reactive agents. J. Exp. Theo. AI., 9(2/3): 237-256.

Brooks R (1986). A robust layered control system for a mobile robot. IEEE J. Robot Autom., 2: 14-23.

Busquets D, Sierra C, Lopez de Mantaras R (2003). A multi agent approach qualitative landmark- based navigation, Auton. Robot., 15(2): 129-134.

Canny JF (1987). The complexity of robot motion planning, Ph.D. dissertation, Department of Electrical Engineering Computer Science, Massachusetts Institute of Technology, Cambridge. MA.

Chatila R, Laumond JP (1985). Position referencing and consistent world modeling for mobile robots. ICRA, 138-145.

Davies T (2007). Path planning and trajectory of collaborative mobile robots using hybrid control architecture. PhD thesis, Faculty of the Royal Military College of Canada.

Du Z, Qu D, Xu F, Xu D (2007). A hybrid approach for mobile robot path planning in dynamic environments. IEEE Int. Conf. Robot. Biomimetics, pp. 1058–1063.

Dupre ME (2007). GA optimized fuzzy control of an autonomous mobile robot. Faculty of Graduate Studies, University of Guelph.

Giralt G, Chatila R, Vaisset M (1984). An integrated navigation and motion control system for autonomous multi-sensory mobile robots. 1st Int. Symp. Robot. Res., pp. 191-214.

Huq R, Mann GKI, Gosine RG (2008). Mobile robot navigation using motors schema and fuzzy context dependent behaviour modulation. Appl. Soft. Comput., 8: 422-436.

Jochem T, Pomerlean D, Kumar D, Armstrong J (1995) PANS: a portable navigation platform. Proc. IEEE Symp. Intell. Vehicles, Detroit, Michigan, September, pp. 107–112.

Kasper M, Fricke G, Steuernagel K, Puttkamer EV (2001). A behaviour-based mobile robot architecture for learning from demonstration.

Robot. Auton. Syst., 34(2-3): 153-164.

Kim G, Chung W (2006). Tripodal schematic control architecture for integration of multi-functional indoor service robots. IEEE Trans. Ind. Electron., 53(5): 1723-1736.

Kolp M, Giorgini P, Mylopoulos J (2006). Multi-agent architectures as organizational structures. Auton. Agent Multi-Agent Syst., 13(1): 3-25.

Konolige K, Myers KL, Ruspini EH, Saffiotti A (1997). The safira architecture: A design for Autonomy. J. Exp. Theo. AI., 9(1): 215-235.

Laird JE, Rosenbloom PS (1990). Integrating execution, planning, and learning in soar for external environments. AAAI, pp. 1022-1029.

Latombe JC (1991), Robot Motion Planning, Kluwer Academic, Dordrecht.

Lindstrom M, Oreback A, Christensen HI (2000). BERRA: A research architecture for service robots. Proc. IEEE Int. Conf. Robot. Autom., 4: 3278-3283.

Minguez J, Montano L (2005). Sensor-based robot motion generation in unknown, dynamic and troublesome scenarios. Robot. Auton. Syst., 52(4): 290-311.

Mitchell J (1986). Planning Shortest Paths. Ph.D. dissertation, Stanford University, Stanford, CA.

Moravec HP, Cho DW (1989). A Bayesian method for certainty grids. AAAI Spring Symp. Robot Navigation, pp. 57-60.

Motlagh ORE, Tang SH, Ismail N (2009). Development of a new minimum avoidance system for a behaviour-based mobile robot. Fuzzy Sets Syst., 160(13): 1929-1946.

Murphy RR (2000). Introduction to AI Robotics. MIT Press London.

Nagatani K, Choset H, Thrun S (1998). Towards exact localization without explicit localization with the generalized Voronoi graph. In: Proc. IEEE Int. Conf. Robot. Autom. Leuven, Belgium, pp. 342–348.

Perez MC (2003). A proposal of a behavior- based control architecture with reinforcement learning for an autonomous under water robot. In Department of Electronics, Informatics and Automation, University of Girona.

Pruski A, Rohmer S (1997). Robust path planning for non-holonomic robots. J. Intell. Robot. Syst: Theory Appl., 18(4): 329-350.

Schwartz JT, Sharir M (1983). On the "piano movers" problem. General techniques for computing topological properties of real algebraic manifolds. Adv. Appl. Math., 4(1): 298-351.

Seraji H, Howard A (2002). Behaviour-based robot navigation on challenging terrain: A fuzzy logic approach. IEEE Trans. Robot. Autom., 18(3): 308-321.

Takahashi O, Schilling RJ (1989). Motion planning in a plane using generalized Voronoi diagrams. IEEE Trans. Robot. Autom., 5(2): 143–150.

Thorpe C (1993). Vision and Navigation: The Carnegi Mellon Navlab, Kluwer, New York.

Vuković N, Miljković Z (2009). New Hybrid Control Architecture for Intelligent Mobile Robot Navigation in a Manufacturing Environment. FME Trans., 37: 9-18.

Weitzenfeld A, Arkin RC, Cervantes F, Peniche JF (1998). Visualization of multi-level Neural-Based Robotic Systems. In Mobile Robot Laboratory Publications, Georgia Institute of Technology.

Yang X, Moallem M, Patel, RV (2006). A layered goal-oriented fuzzy motion planning strategy for mobile robot navigation. IEEE Trans. Syst, Man Cyber Part B: Cybernetics., 35(6): 1214-1224.

Ye C, Wang D (2000). A novel behavior fusion method for the navigation of mobile robots. IEEE Int. Conf. SMC, 5: 3526-3531.

Yavuz H, Bradshaw A (2002). A new conceptual approach to the design of hybrid control architecture for autonomous mobile robots. J. Intell. Robot. Syst., 34(1): 1-26.

Yoichiro E, Arkin RC (2003). Anticipatory Robot Navigation by Simultaneously Localizing and Building a Cognitive Map. Mobile Robot Laboratory, Georgia Institute of Technology.