A New Triple-Based Multi-robot System Architecture and Application in Soccer Robots

Xiangke Wang, Hui Zhang, Huimin Lu, and Zhiqiang Zheng

College of Mechatronics and Automation, National University of Defense Technology, Changsha 410073, China
xkwang@nudt.edu.cn

Abstract. Inspired by the organizational structures of some biological communities and social activities, a new multi-robot system architecture is proposed after the structure of multi-robot system being modeled as a triple $\tau = (I, G, S)$, which consists of the Integrated characters I, the Group characters G and the Single charters S. The proposed system architecture is divided into Integrated Intelligent Layer IIL, Group Intelligent Layer GIL and Single Intelligent Layer SIL sequentially. And then the information flow, the control flow and the response to dynamic environment are all analyzed. At last we report detailedly the application of proposed system architecture in NuBot team, a RoboCup Middle-Size League soccer robots team. In the view of triple-based system architecture, we designed different layers specially by imitating human soccer team naturally. This application, which has been run successfully for three years and is still developing, shows that the proposed triple-based system architecture is adaptable with distinct information/control flow, perfect compatibility and excellent flexibility in dynamic environment.

1 Introduction

Multi-robot systems have been attracted considerable attention in recent years, which naturally extends the research on single-robot systems. Because of intrinsic distribution and parallelism related to sensors and actuators, multi-robot systems have more advantages than single-robot systems, such as they can perform tasks more efficiently, then can accomplish the tasks that single one is disable to execute. Moreover, multiple-robot systems also increase the fault tolerance, provide more flexibility and so on [1–4].

System architecture is an importance issue in multi-robot field, which provides the infrastructure upon which collective behaviors are implemented and determines the capabilities and limitations of the system [5]. Existing system architectures generally fall into two categories: individual architecture and group architecture. The individual architecture mainly focuses on the decisions and the behaviors of the single robot. Many such architectures have been studied such as multi-layer hierarchical structure, behavior-based structure and hybrid structures [6–9]. The group architecture mainly pays attention to the logical

H. Liu et al. (Eds.): ICIRA 2010, Part II, LNAI 6425, pp. 105–115, 2010.

and physical control or information relationships between robots to lead cooperation, including centralized architecture, layered architecture and distributed architecture [1, 5].

Multi-robot system, as an artificial system, essentially imitates the group activities in nature or in society; and moveover the system architecture decides the operational mechanisms and cooperative efficiency of multi-robot system as the action of social institution to human society [1, 10]. Researches on system architecture can parallel to the related results in social-science, life-science and cognitive-science to some extent. In this study, parallel the organizational structure of group activities, we first propose a triple-based system architecture for multi-robot system. And then we report the application of the proposed system architecture in our RoboCup Middle-Size League soccer robots team – NuBot, which has run successfully for nearly three years in many competitions. The application shows that the proposed triple-based system architecture is adaptable with distinct control/information flow, perfect compatibility and excellent flexibility in dynamic environment.

2 System Architecture of Multi-robot Based on Triple

Many individuals in natural or social group-activities can be organized and coordinated well to accomplish the tasks in the dynamic, competitive or cooperative environment, whose organizational structures, especially their perfect adaptability to dynamic environment, are available for multi-robot system architecture.

Let us investigate some lower biological communities with obvious social characters first. Here we take ant or bee colony as examples. Ants or bees build up their unique ways of life in thousands of years, which distinguish them from other inspects. These ways of life are their integrated characters as species. Clear assignments and co-working also exist in ant or bee colony. By implicit or explicit communications, ants or bees cooperate to nest, prey and so on after different tasks are assigned to. These assignments and cooperations reflect their group characters. To accomplish assigned task, each ant or bee performs its respective function, which embodies the single character. Thus the organizational structure of some typical biological communities includes three aspects, viz. integrated character, group character and single character.

In the following we consider some soundly organized social activities, such as football game, basketball game, ... In general, each notable team is branded with special, vivid properties. As soon as these properties are mentioned, the related team will be associated with naturally. These properties are the integrated characters of the teams. When playing, teamwork is necessary for players to defense, score, ... Thus, group character is embodied in the teamwork. Each player shows its skill and specialty in competition, which reflects the single character. Similarly, the organizational structure of some soundly organized social activities also includes integrated character, group character and single character.

From above analysis, we know integrated character, group character and single character are all included in some lower biological communities and soundly organized social activities. This result could be borrowed to propose a new system architecture for multi-robot system. Abstractly multi-robot system could be modeled as a triple $\tau = (I, G, S)$. As an autonomous system, multi-robot system should own its intrinsic property, i.e. integrated character I, which distinguishes multi-robot system with other systems. Capacity of multi-robot system should be larger than single-robot, which means teamwork or group character exists in multi-robot system. G describes this property to embody teamwork into multi-robot system and make multiple robots harmonious. Each robot in multi-robot system is relatively independent and owns itself capacity, which is described by S. Sequentially these three characters foster three kinds of intelligences, namely Integrated Intelligence (II), Group Intelligence (GI) and Single Intelligence (SI). Based on this triple model, multi-robot system architecture can be divided into three layers, viz. Integrated Intelligent Layer (IIL), Group Intelligent Layer (GIL) and Single Intelligent Layer (SIL), as demonstrated in Fig. 1. Each intelligent layer relates to one character in the triple τ. In the following, we will describe the details of three layers.

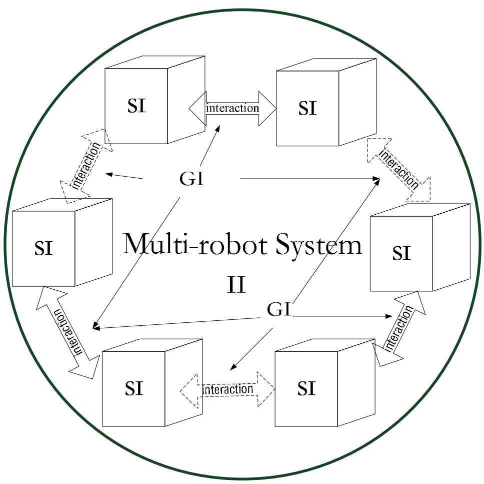


Fig. 1. Multi-robot system architecture based on triple. II: Integrated Intelligence; GI: Group Intelligence; SI: Single Intelligence.

Integrated Intelligent Layer (IIL): This layer addresses designer's expectations to multi-robot system and decides which 'intelligent level' is owned by system. It includes the objectives, performances and preferences of system. Operational mechanisms and basic styles of multi-robot system are also designed in this layer.

Group Intelligent Layer (GIL): This layer ensures the capacity of multi-robot system is larger than that of single-robot system. The environment should be evaluated in real time and different tasks should be decomposed and allocated to each robot after conflict resolutions in this layer. Communications, including implicit and explicit communications, often exist in multi-robot system, which are useful to improve the group intelligence and make the system harmonious. Thus designing proper mechanism for communications is also an important issue in this layer.

Single Intelligent Layer (SIL): Intelligence of single robot embodies in this layer. How to accomplish efficiently the allocated task for single robot is the main task of this layer. It may be with homogeneous or nonhomogeneous robots and can adopt the studies on individual architecture.

This triple-based multi-robot system architecture reflects the organizational structures of some biological communities and social activities to some extent; in the following, we will further design the information flow, the control flow and the response to dynamic environment. Just as that in biological communities or social activities, information flow in triple-based system architecture is bottom-up, i.e. from SIL to IIL (as Fig. 2(a)) and control flow is from IIL to SIL (as Fig. 2(b)). For information flow, single robot senses its environment in SIL, and then abstracts and sends the sensed and itself states to GIL; information from different robots is fused in GIL, and then the valuable part is sent to IIL with the group states. Whereas control flow directs reversely, which is up-down. Basic response to environment is generated in IIL first, and then transferred to GIL; based on the received basic response and the teamwork requirements, tasks of single robot are allocated and transmitted to SIL in GIL; accordingly, single robot plans and accomplishes its received task in SIL. Both the information flow and the control flow are more abstract whereas transferring or controlling frequency is lower in higher layer. The response to dynamic environment of proposed system architecture is as follows. The basic response is decided in IIL, and then in the view of receiving information, adjustments are performed in GIL until varies are fitted. If the vary is out of the range that GIL can deal with, then the new basic response will be regenerated in IIL and new the adjustments are run in GIL, ..., until varies are all fitted well.

3 Application in NuBot Team

In this section, we report the application of triple-based multi-robot system architecture in NuBot team. NuBot team is the RoboCup Middle Size League robot soccer team of National University of Defense Technology and mainly focuses on multi-robot cooperation, robust robot vision, motion control etc [11]. There are eight homogeneous robots in NuBot team, each of which is with omni-directional vision system and omni-directional motion system. Every robot is full autonomous and equipped with notebook, DSP TMS320F2812 control board, encoders and so on. Some NuBot robots are shown in Fig. 3. For convenience, we also develop an ODE-based simulation platform.

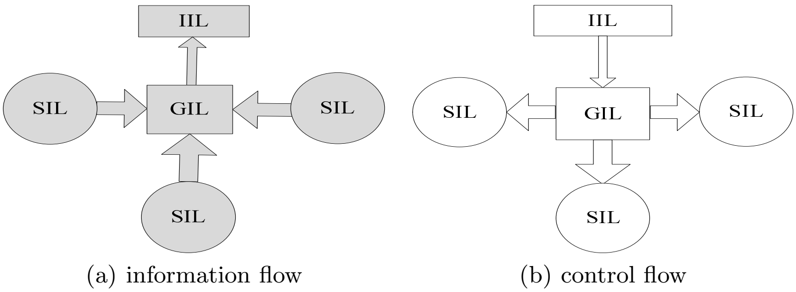


Fig. 2. Information flow and control flow of triple-based system architecture. IIL: Integrated Intelligent Layer; GIL: Group Intelligent Layer; SIL: Single Intelligent Layer.

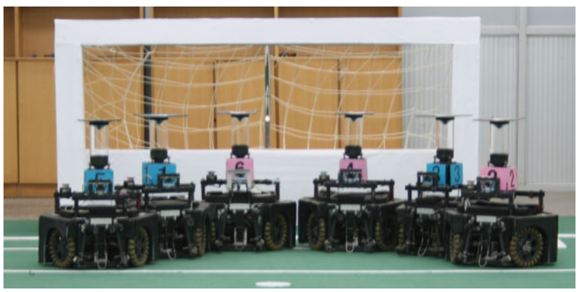


Fig. 3. Robots of NuBot team

3.1 System Architecture of NuBot

We take a specified social actives, human being soccer team, as the natural model of NuBot team. An obvious fact is that human being soccer team is much more intelligent than robot soccer team currently, thus the inspiration is rational. Inspired by the organizational architecture of human being soccer team, we materialize the triple-based system architecture in NuBot. In the following, we elaborate the design of Integrated Intelligent Layer, Group Intelligent Layer and Single Intelligent Layer one by one.

Integrated Intelligent Layer. Integrated Intelligent Layer is also called Coach Layer straightforward in this study, because it mainly imitates the coach's intelligence. In human being soccer team, the coach responds to decide the basic strategy aiming at different opponents before the game begins, and adjusts the statics real time in the game. So, Coach Layer of NuBot includes two aspects: Out-Field Coach and In-Field Coach. Out-Field Coach responds the basic strategy imitating the coach's arrangements before game. Till now, three strategies are designed in NuBot, which are Attack First, Defence First and Balance between Attack and Defence. And eight roles are contributed, which are Goalkeeper, Attacker, Passive, Mid-Field, Acid-Passive, Assistant, Blocker and Gazer. The number of the roles (equals 8) is always more than the number of active robots (no more than 6), so different role sets can be assigned to realize different strategies by Out-Field Coach. In-Field Coach evaluates the states between opponents and teammates and then adjusts the statics in the game. A simple adjustment in NuBot is: if the score keeps ahead and the remaining time is not too long, the 'Defence First' strategy will be chosen by priority; accordingly if the score keeps behind and the remaining time is not too long, the 'Attack First' strategy will be chosen.

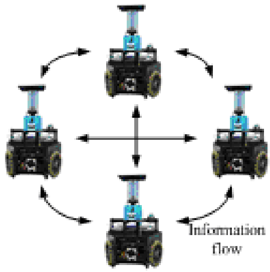
Group Intelligent Layer. Group Intelligent Layer mainly imitates the captain or the decision-maker in the field. It allocates the roles of the robots and initiates the cooperation.

A hybrid distributed role allocation method is developed for NuBot, which includes role performance evaluation, assignment based on rule and dynamic application. Every robot firstly evaluates the costs of being treated as Attacker and Passive for itself and all the other active robots, and selects the most proper robots as Attacker and Passive [12]. Then, the remaining roles are assigned based on rules [13]. At last, the dynamic application is used to avoid the repeated role assignments for the inconsistent information between different robots.

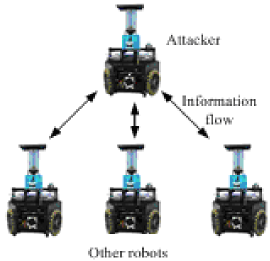
Cooperation includes implicit cooperation and explicit cooperation in NuBot. All robots maintain a common world model. And in implicit cooperation, robots realize cooperations by sharing the information in the world model. Taking 'defence action' as an example. Each active robot decides its defensive action based on its self-location, the distance to ball and the teammates' actions in the sharing world model. Every robot is equal in implicit cooperation and the information flows between robots are shown as Fig. 4(a). In explicit cooperation, robots complete cooperations by direct communication. The cooperation is initiated by one of the robots, called initiator. The initiator selects and informs one or more teammates to complete the tactics. When the tactics is finished, the cooperative relationship relieves immediately. For example, the tactics of free kick in NuBot team is an explicit cooperation. Robots are not equal in explicit cooperation and initiator dominates the cooperation. The information flows of explicit cooperation are shown as Fig. 4(b).

Single Intelligent Layer. Single Intelligent Layer imitates the single player, and is driven by role. Single Intelligent Layer executes different action according to the role allocated by Group Intelligent Layer or the action assigned in explicit cooperation. The structure of Single Intelligent Layer is shown as Fig.5, which includes Sensor Hierarchy and Action Hierarchy [14]. Sensor Hierarchy processes the data from different sensors, constructs and maintains the World Model. Action Hierarchy controls the robot to complete the tasks.

Action Hierarchy is divided into four different parts, and each part includes different intelligence and complexity behavior sets. The four parts are Action



(a) implicit cooperation



(b) explicit cooperation

Fig. 4. Information flow in NuBot Team

Selection, Senior Action, Basic Behavior and Motor Control. Every part gets its required information from World Model respectively and is just influenced by the lower part.

Information Flow and Control Flow. Information flow and control flow are both important issues for system architecture. The information flow is from bottom (SIL) to up (IIL), just as the analysis in above section. Especially, information in SIL flows more and more abstractly from bottom to up in Sensor Hierarchy too. The lowest includes the original information obtained from different sensors. Low World Model includes the basic knowledge abstracted from original information, such as the robot self-location, the teammates' locations, the ball's position and the obstacles' positions. High World Model abstracts further the information from Low World Model, which includes the ball trace estimation, the ball speed estimation and so on. GIL includes information from different robots and then fuses to obtain the teammates' and enemies' locations, the exact ball's location, which robot is controlling or will control ball and what are the current roles of teammates, ..., . IIL records and deals with the highest-level information such as the team's strategy, states or scores. Control commands direct from IIL to SIL. Which strategy (Attack First, Defence First, and Balance between Attack and Defence) should be performed is selected in IIL, that is the basic response for NuBot in competitions. Based on the selected strategy, roles are allocated to every robot in GIL. And at last every robot selects its behavior and runs action according to its role. Obvious, distinct information flow and control flow exist in this system architecture.

3.2 Application in Competition

Triple-based system architecture was developed in NuBot Team from 2007 and now is still developing. Since 2007, NuBot Team has participated in RoboCup 2008 Suzhou and RoboCup 2009 Graz with entering the second round each time. It also took part in RoboCup China Open 2007 - 2009 and wined the first-place prizes in 2007, 2008, third-place in 2009. These achievements are certainly

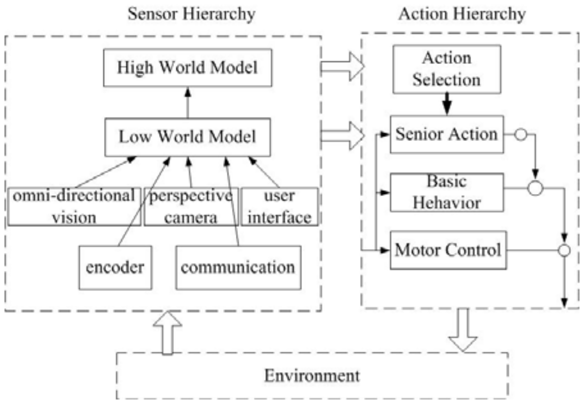


Fig. 5. The structure of Single Intelligent Layer

dependent on the whole of multi-robot system, including mechanism, sensing, control and so on; whereas there is no denying that this triple-based system architecture also plays an importance role. This architecture can adopted in such a complex and dynamic completion, which proves its excellent flexibility in dynamic environment. In the three-year developing, different ideals and plans are embodied in this frame with perfect compatibility. To report clearly the effect of proposed system architecture, we catch and explain some typical scenarios from our ODE-based simulation first.

In Fig. 6, items marked by red-oval are the strategies appointed in Coach Layer; and items marked by blue-box are the roles allocated in GIL and the senior behaviors selected in SIL. There are different appointed strategies or different robot numbers in these four scenarios. Fig. 6(a) shows a typical scenario that 6 active robots with the 'Balance between Attack and Defence' strategy appointed by Coach Layer. Sequentially, six roles are allocated for these robots automatically in GIL, which are Goalkeeper, Attacker, Passive, Mid-Field, Acid-Passive and Blocker. Fig. 6(b) also shows 6 active robots scenario, whereas the appointed strategy is 'Attack First'. The role Blocker is removed and role Assistant is added by GIL accordingly. The scenario in Fig. 6(c) is appointed the same strategy as that in Fig. 6(a), but just with 5 active robots, thus the role Blocker disappears. Fig. 6(d) shows 4 active robots with 'Defence First' strategy scenario, in which the allocated roles are just Goalkeeper, Attacker, Passive and Acid-Passive. These scenarios show different roles are allocated with different strategies and robot numbers to adapt different competitions. So system architecture in NuBot reflect the intelligences of Coach Layer and GIL in some sense.

In Fig. 6, yellow circles in green field represent robots. The centers of circles mean robots' locations and the red radiuses directed from centers mean robots' attitudes. Teamwork between multi-robots are reflected from the distribution of robots' locations and attitudes. For example, scenarios in Fig. 6(a) and 6(c)

(a) 6 robots with 'Balance between Attack and Defence' strategy

(b) 6 robots with 'Attack First' strategy

(c) 5 robots with 'Balance between Attack and Defence' strategy

(d) 4 robots with 'Defence First' strategy

Fig. 6. Typical scenarios of applying triple-based system architecture in NuBot

show multiple robots attack as a team and scenario in Fig. 6(b) shows multiple robots defense as a team. These cooperations are all implicit. Playing free kick with multiple robots is shown in Fig. 6(d), in which robot 3 shoots after the ball is push gently to by robot 4. Obviously, the cooperation in this scenario is explicit.

The blue-box marked items also explain the senior behaviors selected in SIL in Fig. 6. For example, when multiple robots attack as a team in Fig. 6(a), the selected action of Attacker is 'shoot', i.e. dribbling and preparing to shoot; the selected action of Mid-Field is 'protect ball', i.e. protecting the ball not to catch by enemy; ... . Every robot will select different senior action in different situation automatically.

System architecture of NuBot also works well in competitions. Here we give two scenarios caught from the video of the final in RoboCup China Open 2008. (see `http://www.tudou.com/programs/view/8XCpS44yX18/`).

Fig. 7(a) shows three robots initiate their attack, where Attacker dribbles the ball, Acid-Passive protects the ball and Passive positions rightly to block the enemy. Fig. 7(b) shows the free kick tactics, where Mid-Field pushes the ball gently to Attacker, and then Attacker shoots. Acid-Passive is in right position to protect the ball. These two scenarios exhibits partly the proposed system architecture work well in practise and adapt in dynamic environment.

(a) three robots attack as a team (b) free kick with multiple robots

Fig. 7. Typical scenarios of NuBot Team in Competition

4 Conclusion

Paralleled to the organizational architecture of some biological communities and social activities, we proposed a new triple-based multi-robot system architecture and reported its application in NuBot Team. The triple $\tau = (I, G, S)$ consists of the Integrated characters I, the Group characters G and the Single charters S; system architecture is divided into Integrated Intelligent Layer, Group Intelligent Layer and Single Intelligent Layer sequentially. An implementation of the proposed system architecture, which has been run successfully for three years and is still developing, is elaborated. We design the IIL, GIL and SIL in NuBot team by imitating human being soccer team naturally. The application in simulations and competitions shows that proposed triple-based system architecture is adoptable with distinct control/information flow, perfect compatibility and excellent flexibility in dynamic environment.

References

1. Tan, M., Wang, S., Cao, Z.Q.: Multi-robot System. Tsinghua University Press, Beijing
2. Zhang, F., Lin, L.M.: Architecture and related problems concerning cooperative mobile robot system. Robot 23(6), 554–558 (2001)
3. Arkin, R.C., Balch, T.: Cooperative multiagent robotic systems. In: Artificial Intelligence and Mobile Robots. MIT/AAAI Press, Cambridge (1998)
4. Yuan, K., Li, Y., Fang, L.X.: Multiple mobile robot systems: A survey of recent work. Acta Automatica Sinica 33(8), 785–794 (2007)
5. Cao, Y.U., Fukunaga, A.S., Kahng, A.B.: Cooperative mobile robotics: Antecedents and directions. Autonomous Robotics 4(1), 7–27 (1997)
6. Saridis, G.: Toward the realization of intelligent controls. Proceedings of the IEEE 67(8), 1113–1115 (1979)
7. Brooks, R.A.: A robust layered control system for a mobile robot. IEEE Journal of Robotics and Automation 2(1), 14–23 (1986)
8. Arkin, R.C.: Motor schema-based mobile robot navigation. The International Journal of Robotics Research 8(4), 92–112 (1998)

9. Connell, J.H.: Sss: A hybrid architecture applied to robot navigation. In: Proceedings of the 1992 IEEE Conference on Robotics and Automation, Los Alamitos, pp. 2719–2724 (May 1992)
10. Gao, Z.J., Yan, G.Z., Ding, G.Q., Yan, D.T., Chen, Z.Z.: Current status and development of multirobot coordinative and cooperative systems. Optics and Precision Engineering 9(2), 99–103 (2007)
11. Zhang, H., Wang, X., Lu, H., Ji, X.: Nubot team description paper 2009. In: RoboCup 2009 Graz, Graz, Austria (2009)
12. Liu, L., Ji, X.C., Zheng, Z.Q.: Multi-robot task allocation based on market and capability classification. Robot 28(3), 338–343 (2006)
13. Ji, X.C., Cui, L.H., Zheng, Z.Q.: Application of a hybrid distributed multi-agent task allocation mechanism to soccer robot system. Computer Application 28(3), 706–709 (2008)
14. Ji, X.C., Liu, L., Zheng, Z.Q.: A modular hierarchical architecture for autonomous robots based on task-driven behaviors. In: Proceedings of the International Conference on Sensing, Computing and Automation, Chongqing, China, pp. 631–636 (May 2006)