Proceedings 2005 IEEE International Symposium on
Computational Intelligence in Robotics and Automation
June 27-30, 2005, Espoo, Finland

Path Planning Protocol for Collaborative Multi-Robot Systems

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***Abstract*— Wireless ad hoc sensor networks are being developed to collect data across the area of deployment. These technologies enable multiple robots to form a temporary *multi-robot* team and cooperate with each other to launch a complex mission. A path planning algorithm and well-organized communication protocol are needed when the multi-robot systems have to search for or reach a designate target. It is more complex in designing a collaborative path planning algorithm and communication protocols for multi-robot systems since it has to consider avoiding intra-team collisions, energy efficiency, information sharing and cooperation problems, etc. Moreover, unlike single robot path planning problem, a multi-robot system is usually constructed by several simple, cheap, function-restricted, and energy-limited robots to plan a path toward the target by cooperative fashion. This is the main advantage of the puny multi-robot system. Therefore, in this paper, we propose a simple but efficient collaborative path planning algorithm (CPPA) and a communication protocol for the sensor multi-robot systems where the energy consumption is reduced as well as the duration of reaching the goal is shortened. Moreover, considering the survivability of the mission, the proposed algorithm can enable the sensor robots to complete the mission even if some robots are failed by accidents. Experiment results show that the energy consumption and computation of proposed algorithm is lower than the multiple independent robots or other methods.**

I. INTRODUCTION

There are many popular researches about sensor networks in recent years [10], [14], [22]. The character of sensors that it can detect the information of the specified regions where we are interested like humidity, brightness, degree of shake, and so forth [2], [7]. Besides, with the advances in wireless ad hoc communication and robotics technology, it can be possible to organize teams (swarms) of the autonomous multiple sensor robots to finish complex missions that comprise several teams [9]. These sensor robots generally cooperate with each other to complete an assigned mission and use collaborative strategy for power saving, increasing the survivability, and improving the successful probability of the mission, etc.

The path planning problems had been discussed for several decades, because that this problem is an essential research issue in robotics since robots need to plan a path to reach a goal. General speaking, the path planning problems are classified as two categories: known-environment path planing (KEPP) and unknown-environment path planning (UEPP). The KEPP methods assume a complete knowledge of both the robots and the environment [8], [19], [23]. Its main advantage is to prove the existence of a solution that permits the robot to reach its destination and to generate collision-free map-making. However, they have some well-known drawbacks that these proposed model need the exact model of the environment and is difficult to handle correctly dynamic modifications of the the environment due to the addition of objects and presence of obstacles with mobility.

On the contrary, some researches about the unknown environment and single robot scenario [6], [11], [24], UEPP incorporates and reflects the sensing information to a robot's planning process as apposed to classical motion planning. Therefore, an absolute localization is not required between the robots and the environment. In these circumstances, the robots has to acquire through its sensory inputs a set of stimulus-response mechanisms instead of a structural modeling of the environment. In this scheme, the robot is generally expected to carry out simple tasks. Nevertheless, these methods are only operated in a single robot system. The reason of using multiple robots is to prevents the robots break down in their mission-executing for increasing the survivability. There is also a drawback about energy that every robot needs to do the same calculations and decision-making in the single robot system. Although many methods of path planning in unknown environment have been proposed for multi-robot system [1], [3], [5], [25]. They seldom consider the power saving as well as the complexity of the method in this system. Therefore, we propose a power-efficient path planning protocol named collaborative path planning algorithm (CPPA) for multi-robot to operate easily in unknown environment. The decision of path planning in CPPA is decided by a coordinator of a cluster with the environmental information sensed by other member robots. With the cooperation of the coordinator and members, the cluster can reduce the communication to reach their destination.

The remainder of paper is organized as follows. Section II describes the related technologies and architecture of multi-robot system. In Section III, we propose a concept of the protocol standard with minimap to help the decision-making of the coordinator. Then, in Section IV, we present our proposed CPPA for implementation of this protocol. We perform a series simulation models to evaluate the proposed algorithm in Section V. Finally, we give some conclusions in Section VI.

II. COLLABORATIVE MULTI-ROBOT SYSTEM

Fig. 1 shows a sketch of multiple sensor robots scenario searching for a target in an unknown environment with many obstacles and needing a collision-free path planning algorithm to go to the target. These mobile robots equips several sensors and wireless communication equipments. There is no global

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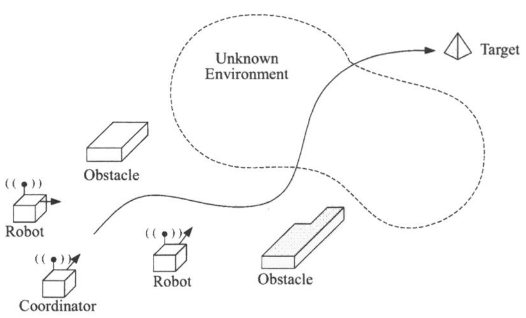


Fig. 1. An illustration of the path planning in unknown environment with multiple sensor robots

positioning system (GPS) since all sensor robots are in indoor environment, and needs indoor position estimation methods to indicate the position. Most existing localization algorithms make use of trilateration or multilateration based on range measurements obtained from received signal strength indicator (RSSI) [4], time of arrival (ToA) [20], time difference of arrival (TDoA) [18], and angle of arrival (AoA) [17]. The RSSI technique is employed to measure the power of the signal at the receiver and, because of its simplicity, it is considered in our work.

These sensor robots are organized as a team and one of them plays a coordinator. The others serve as members and they communicate with each other by wireless devices. The coordinator is like a guider to lead their members to go to the target. The communication protocol is IEEE 802.15.4 [12], which is a low cost and low energy consumption equipment for short range (≈ 10 meters in indoor environment) communications. In the aspect of the direction measurement of the robots, each sensor robot equips a electronic compass, which can support a global direction of the robot, to indicate its current direction [21]. With the electronic compass, the sensor robots can know which direction they face. The direction of the robot d is easily represented as an angular magnitude by electronic compass.

Besides, the inter-distance of robots in a cluster should be maintained to avoid collisions or wandering away. We consider a cluster consisting of n sensor robots $R_1, R_2, \ldots, R_n$ and D_{ij} represents the distance between two sensor robots R_i and R_j. The robot collision avoidance problem can be considered same as the obstacle avoidance by using several techniques such as infrared [15] and ultrasound [16], etc. These techniques are designed to overcome the collision problems but not wandering away problem. We use the RSSI value η to estimate the distance between two robots [13]. The RSSI value can be obtained by received communication packet from other robots.

If the measured signal strength η_i from the received packet exceeds that of the robot R_i by a threshold h, we say that the robot R_i is in the lower boundary range. Otherwise, the R_i is wandering away from the coordinator and should be pulled back. To maintain the distances between the coordinator and its members, the coordinator periodically broadcasts a beacon B with its coordinate to its members. To avoid the *ping-pong effect* of using the threshold, we set two thresholds – the upper bound h_u and the low bound h_l. Each robot, after receiving the beacon, will judge the η_i whether smaller than the h_l. If $\eta_i < h_l$, the robot R_i will turn it direction and goes toward the coordinator until the η_i is larger than or equal to the h_u.

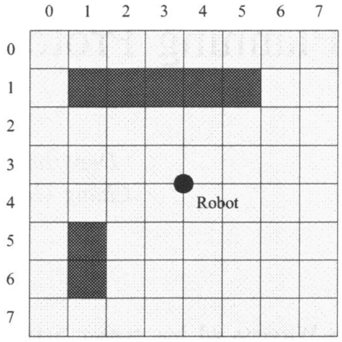


Fig. 2. The example of 8×8 fixed structural minimap with obstacles for a robot in unknown environment.

columns	length
Source_ID_Num	4 bits
Destination_ID_Num	4 bits
X-Coordinate	10 bits
Y-Coordinate	10 bits
Enviornmental Data	var bits

Fig. 3. The packet format of the minimap sending from the members to their coordinator.

III. MINIMAP INTEGRATION

At the Section II, we have known that the coordinator collect the information of the environment from its members for maintaining the global map information to help itself do decision-making of path planning. Therefore, we should know the packet format of the data communication between the coordinator and the members. So in this section, we try to make the sensing data of environment a fixed packet format. There are two packet format of communication for the coordinator and the members. One packet format is for the member to send information of environment to its coordinator, and the other is for the coordinator to request the members to gather their information of the environment. With this format, the robots can more easily do communication with others in a common protocol.

First, we define a fixed 8×8 minimap model to represent the environmental data of a robot in its coverage. In Fig. 2, a robot fills the grids with the color (environmental data = 1) if it sense the obstacle in it. The robot can adjust the size of $n \times n$ minimap according to the number of sensors the robot have. Therefore, we make the information of minimap into a fixed packet with 64 (8×8) bit streams. For example, the 64 bits environmental data of the robot in Fig. 2 are "00000000, 01111100, 00000000, 00000000, 00000000,

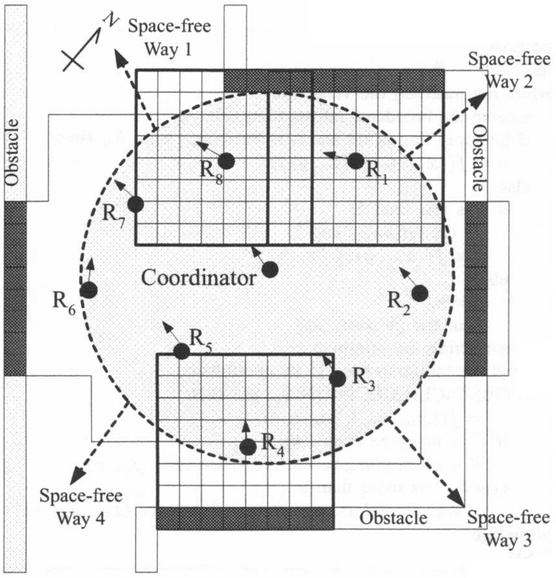


Fig. 4. The members sense the information of environment integrated by the coordinator and decide all the free-space ways.

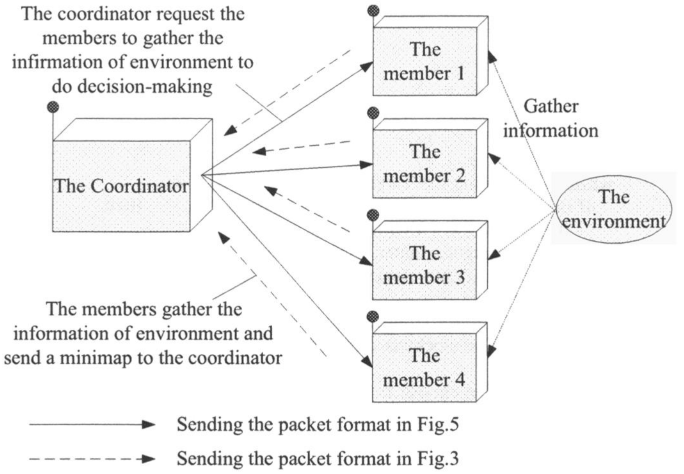


Fig. 6. The sketch of communication model between the coordinator and its members.

columns	length
Source_ID_Num	4 bits
Destination_ID_Num	4 bits
Command_Type	2 bits
X-Coordinate	10 bits
Y-Coordinate	10 bits
Compass_Direction	9 bits

Fig. 5. The packet format of the request sending from the coordinator to its members.

01000000, 01000000, 00000000" respectively. So we can make the sensing data a packet format in Fig. 3. This packet format is used for the members to sending the information of environment to the coordinator. In this packet format, the column of Source_ID_Num and Destination_ID_Num are filled with the id number of the member itself and its coordinator. And the column of X-Coordinate and Y-Coordinate contain its coordinate. The environmental data are extended into the last column of the packet with adjustable fixed bits.

After defining the minimap model, the robots can easily send and the coordinator can correctly recognize its sensing information by the standardized packet format. The Fig. 4 is the sketch of the environmental shape integrated by the coordinator in path planning. The coordinator receives all standardized minimaps of its members where it is interested to build the partial view of the environment to check all the space-free ways for decision-making. Therefore, the packet format for the coordinator is in Fig. 5. In this packet format, the Source_ID_Num is filled with the id number of the coordinator, and Destination_ID_Num is filled with the id number of member needs to gather the information of the environment. If the message of coordinator needs to broadcast to all the members in its cluster, the column of the Destination_ID_Num is contain "1111" (reservation for broadcasting). There are three commands in the Command_Type column of the packet that we can categorize with its command actions. The Command_Type = 00 represents the broadcast message (or beacon) with unchanged direction of its cluster, and the Command_Type = 01 is also the broadcast message but with changed direction of its cluster. The last, the Command_Type = 11 is used by the coordinator to gather the information of environment from the specified id robots in the column of the Destination_ID_Num. And the column of X-Coordinate and Y-Coordinate are the coordinator's coordinate. The last column is used for containing the degree of the coordinator's angle by its electronic compass. Using these two fixed packet format, the coordinator and members can easily request for and transmit with the environmental information to each other.

IV. INTRA-TEAM COMMUNICATION PROTOCOL

By the integration of the minimaps, we can clearly construct the communication model in Fig. 6 between the coordinator and the members. Therefore, in this section, we describe the proposed collaborative path planning algorithm (CPPA) with intra-team communication protocol in detail. Taking Fig. 4 for example, there are nine sensor robots ($n = 9$) gathered as a cluster to cooperate with each other to go to a given target. First, R_c receives the (x_t, y_t) of the target and calculates the angular magnitude to the target and to turn its direction to the target. The R_c then broadcasts its members a request packet including the target's coordinate (x_t, y_t), its coordinate (x_c, y_c), and the facing direction to request its members to collect related map information. The member $R_i, i \in \{1, \ldots, n-1\}$, after receiving the request packet, will collect the related environment information and reply its minimap including the shapes of obstacles if any and its coordinate (x_i, y_i) back to R_c.

THE COORDINATOR ALGORITHM

```
BEGIN
turn_left_counter ← ∅
turn_right_counter ← ∅
set Command_Type ← 11
$v = f((x_c, y_c), (x_t, y_t))$
broadcast $((x_c, x_c), v)$
while not reaching the Target or receive the $M_m$ do
  if detecting an obstacle from sensor robots $(x_o, y_o)$ then
    if OBSTACLE_DECISION($x_o, y_o$) then
      if turn_right_counter flag is set then
        $v'$ = counterclockwise_choose_free_space $(x_c, y_c, v)$
      else
        if turn_left_counter flag is set then
          $v'$ = clockwise_choose_free_space $(x_c, y_c, v)$
        else
          $v'$ = choose_free_space $(x_c, y_c)$
          if $v'$ is no more than $v$ and turn_left_counter is not set then
            set the turn_left_counter flag
          else // $v'$ is more than $v$ and turn_right_counter is not set
            set the turn_right_counter flag
      set Command_Type ← 01
    else
      clear the turn_left_counter and turn_right_counter flags
      set Command_Type ← 00
  stack $((x_c, y_c), v) \leftarrow ((x_c, y_c)', v')$
  broadcast $((x_c, y_c), v)$
endwhile
END
```

Fig. 7. The algorithm of the coordinator process.

THE MEMBER ALGORITHM

```
BEGIN
far_away ← ∅
while not reaching the Target do
  receive the broadcast information $((x_c, y_c), v)$
  if far_away flag is set and $\eta$ is not bigger than $h_u$ then
    $v = f((x_m, y_m), (x_c, y_c))$
  else
    if $\eta$ is less than $h_l$
      set the far_away flag
      $v = f((x_m, y_m), (x_c, y_c))$
    else
      $v = v_c$
      clear the far_away flag
  constructing the minimap
  send the minimap back to its coordinator
  if OBSTACLE_DECISION($x_o, y_o$) then
    $v' = f((x_m, y_m), (x_c, y_c))$
    if $v'$ is no more than $v$ then
      $v'$ = clockwise_choose_free_space $(x_m, y_m, v)$
    else // $v'$ is more than $v$
      $v'$ = counterclockwise_choose_free_space $(x_m, y_m, v)$
endwhile
END
```

Fig. 8. The algorithm of the member process.

The coordinator will wait for a while or its countdown expired to collect all the minimaps from its members to build up a temporary view of the environment for making decision. According to the (x_i, y_i) and the fixed structural model of minimap, the coordinator can determine which of locality R_i is. The coordinator combines different minimaps from its members, it can build a temporary map as shown in Fig. 4. The R_c then, according to the v and several possible space-free ways, chooses the nearest (with high priority) space-free way to the target to make a smarter decision.

The direction will be changed while the team meets an obstacle. Since the CPPA is based on cooperative fashion, the members will send the minimaps to the coordinator if they meet obstacles. Thus, when R_i runs into a obstacle in a straight direction, it will announce its minimap to R_c for the decision making. When R_c receives the address of a obstacle, it will update its map information and determine whether they have to change a new direction or not. If R_c decides to change a new direction, it will broadcast this new information to its members with the new direction (set Command_Type = 01) and its current coordinate (x_c, y_c). Thus, members will move toward the new direction announced by R_c if they have exceeded the (x_c, y_c). If R_c does not change a new direction (the column of Command_Type is still 00), R_i will avoid the obstacles and get closer to R_c when its new direction has no obstacles. The algorithms of the coordinator and members are shown in Fig. 7 and Fig. 8, respectively.

These processes are proceeded interactively until they reach the goal.To alleviate the energy consumption, the direction to the target is computed by coordinator only and the members follow the direction to go to the goal. They only needs to maintain its minimap and avoid the obstacles they meet. The communication overhead is also reduced since members only communicate with the coordinator when they meet the obstacle in its straight direction.

V. EXPERIMENT RESULTS

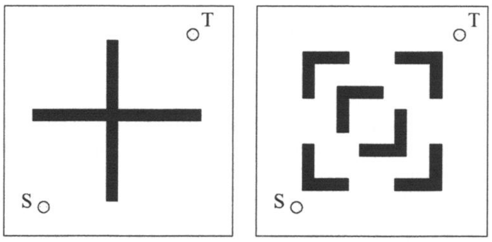
To illustrate the efficiency of the proposed CPPA on the path planning of multi-robot systems, we perform a series of simulation scenarios to evaluate the performance of the CPPA. We perform four different scenarios, shown in Fig. 9, to evaluate the CPPA. These simulation scenarios have individual characters, such as cross-shaped obstacles, double frame-shaped obstacles, and other easily trap-making mazes. Initially, ten mobile sensor robots are randomly distributed in the left-down corner in the simulation area. One of them serves as the coordinator and the others serve as cluster members. The target is assumed in the right-up corner of the area. The simulation parameters are shown in Table I.

TABLE I

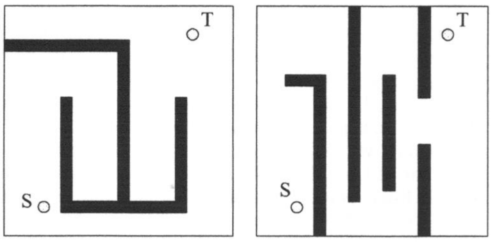
SYSTEM PARAMETERS IN SIMULATIONS

Simulation Parameter	Normal Value
Radio data rate	250 kb/s
Radio transmission range	10 m
Radio transmission power	1400 mW
Radio receiving power	1000 mW
Radio idling power	830 mW
Radio sleeping power	130 mW
CPU clock rate	400 MHz
Computation power	500 mW
Ultrasound sensing range	1 m
Simulation map length	1000 m
Simulation map width	1000 m

For the simplicity of representation, we use a black point to represent the cluster. The movement of the cluster is presented by using series points. Fig. 10 shows the experiment results

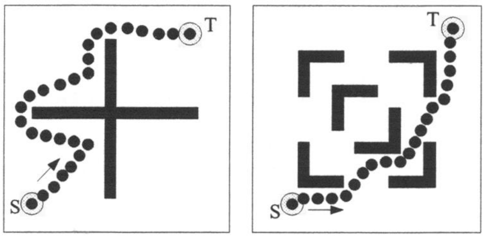


scenario 1 (s1) scenario 2 (s2)

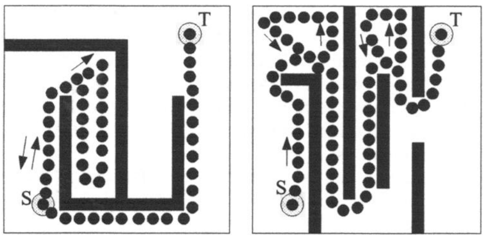


scenario 3 (s3) scenario 4 (s4)

Fig. 9. Four scenarios of the simulation.



scenario 1 (s1) scenario 2 (s2)



scenario 3 (s3) scenario 4 (s4)

Fig. 10. The moving path of a cluster of multi-robot by using CPPA.

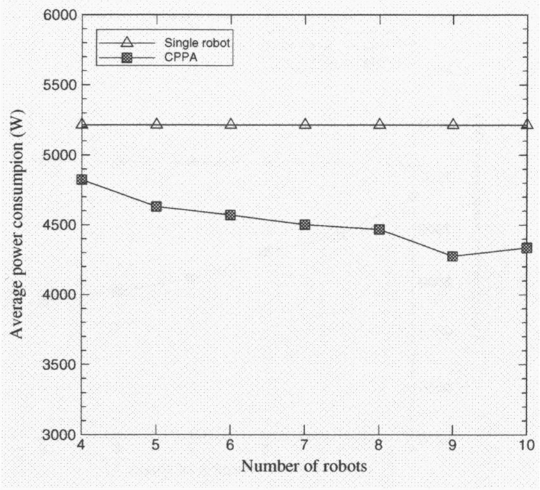


Fig. 11. The comparison of the multi-robot by CPPA and single robot in the designed s1 scenario.

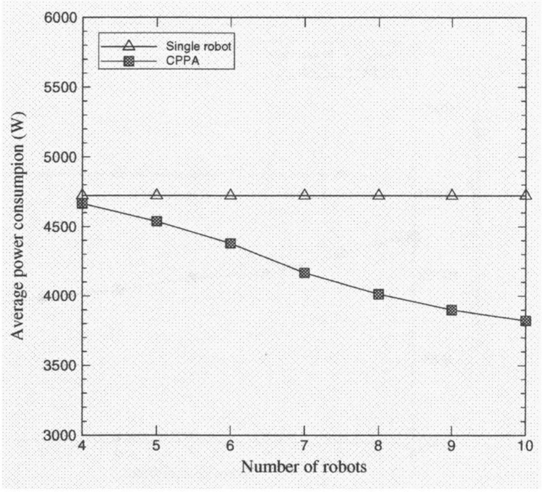


Fig. 12. The comparison of the multi-robot by CPPA and single robot in the designed s2 scenario.

by our simulation in the four different scenarios. We can see that the proposed CPPA leads the robots toward the target smoothly. Moreover, in scenario 3 and 4, we can see that, base on the CPPA, initially the coordinator plans a wrong path to the target by decision making. However, the CPPA will collect the environment information to adapt their moving path to reach the target correctly.

To compare the energy efficiency of the CPPA with other single robot path planning algorithms. At last simulation, we try to make a comparison of average energy consumption with a single robot. The energy consumption in the CPPA includes decision-making computation (only in coordinator), wireless communication (transmission, receiving, idling, and sleeping), and movement, but the energy consumption in general single robot only includes decision-making computation and movement. We try to considerate all the possible energy consumptions in real environment to make the simulation more realistic. Fig. 11, Fig. 12, Fig. 13, and Fig. 14 show the average energy consumption of each robot by the CPPA and single robot in the four scenarios, respectively. We can see that the power consumption of each robot by using the CPPA is more lower than the single robot system when the number of the cluster is increasing. The power consumption is getting lower when the number of robots in a robot team increases. This is because that CPPA adopts cooperative strategy to plan a path to the given target and thus reduces the power consumption by one single robot.

VI. CONCLUSIONS

In this paper, we propose a power-efficient path planning protocol named collaborative path planning algorithm (CPPA) for a multi-robot system without global positioning

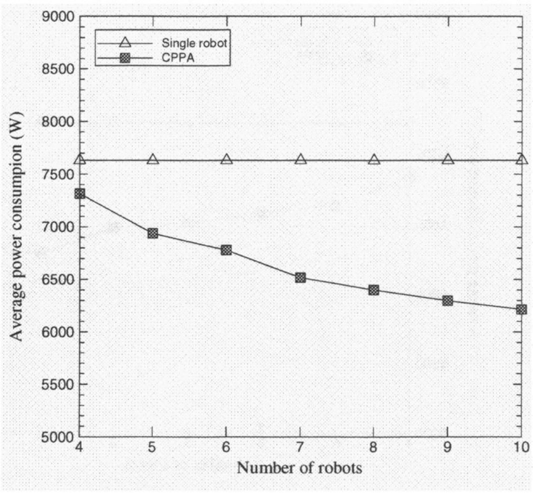


Fig. 13. The comparison of the multi-robot by CPPA and single robot in the designed s3 scenario.

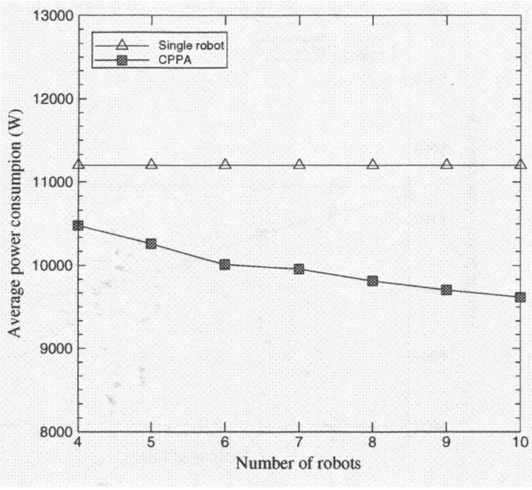


Fig. 14. The comparison of the multi-robot by CPPA and single robot in the designed s4 scenario.

system (GPS). The energy consumption is reduced by using a structural model of protocol and a cooperative fashion of multiple mobile robots. Comparing to the signal robot system, multi-robot system can enhance not only the performance of execution but the survivability. Experiment results also show that the proposed CPPA gets lower energy consumption than those robots without teamwork.

ACKNOWLEDGEMENT

This work was supported in part by the National Science Council, Taiwan, R.O.C., under Contract NSC93-2213-E-182-022.

REFERENCES

[1] R. Alami, S. Fleury, M. Herrb, F. Ingrand, F. Robert, "Multi-Robot Cooperation in the MARTHA Project," *IEEE Robot. Automat. Mag.*, vol. 5, no. 1, pp. 36–47, Mar. 1998.

[2] P. Bergamo et al., "Collaborative Sensor Networking Towards Real-Time Acoustical Beamforming in Free-Space and Limited Reverberance," *IEEE Trans. Mobile Computing*, vol. 3, no. 3, pp. 211–224, July 2004.

[3] S. Boonphoapichart, S. Komada, T. Hori, and W.A. Gruver, "Robot Motion Decision-making System in Unknown Environments," in *Proc. IEEE ICRA-2003*, vol. 3, pp. 4197–4202, Taipei, Taiwan, Sept. 2003.

[4] N. Bulusu, J. Heidemann, and D. Estrin, "GPS-less Lowcost Outdoor Localization for Very Small Devices," *IEEE Personal Commun.*, vol. 7, no. 5, pp. 28–34, Oct. 2000.

[5] Z. Cao, L. Xie, B. Zhang, S. Wang, and M. Tan, "Formation Constrained Multi-robot System in Unknown Environments," in *Proc. IEEE ICRA-2003*, vol. 1, pp. 735–740, Taipei, Taiwan, Sept. 2003.

[6] W. Chen, C. Fan, and Y. Xi, "On-line Safe Path Planning in Unknown Environments," in *Proc. IEEE ICRA-2003*, vol. 3, pp. 4191–4196, Taipei, Taiwan, Sept. 2003.

[7] W.-P. Chen, J.C. Hou, and Lui Sha, "Dynamic Clustering for Acoustic Target Tracking in Wireless Sensor Networks," *IEEE Trans. Mobile Computing*, vol. 3, no. 3, pp. 258–271, July 2004.

[8] J.L. Diaz de Leon S. and J.H. Sossa A., "Automatic Path Planning for a Mobile Robot among Obstacles of Arbitrary Shape," *IEEE Trans. Syst., Man, Cybern. B*, vol. 28, no. 3, pp. 467–472, June 1998.

[9] M. Gerla and Y. Yi, "Team Communications among Autonomous Sensor Swarms," *ACM SIGMOD Record*, vol. 33, no. 1, pp. 20–25, Mar. 2004.

[10] P. Havinga, J.C. Hou, and F. Zhao, "Wireless Sensor Networks," *IEEE Wireless Commun.*, vol. 11, no. 6, pp. 4–5, Dec. 2004.

[11] A.M. Hussein and A. Elnagar, "A Low Cost Path Planer in Unknown Environments for Autonomous Mobile Robots," in *Proc. IEEE Int. Symp. CIRA-2003*, vol. 2, pp. 724–728, Kobe, Japan, July 2003.

[12] IEEE 802.15.4 Working Group, "Part 15.4: Wireless Medium Access Control (MAC) and Physical Layer (PHY) Specifications for Low Rate Wireless Personal Area Networks (LR-WPANs)," ANSI/IEEE Std 802.15.4, Feb. 2003.

[13] K.-I. Itoh, S. Watanabe, J.-S. Shih, and T. Sato, "Performance of Handoff Algorithm Based on Distance and RSSI Measurements," *IEEE Trans. Veh. Tech.*, vol. 51, no. 6, pp. 1460–1468, Nov. 2002.

[14] P. Julian, A.G. Andreou, L. Riddle, S. Shamma, D.H. Goldberg, and G. Cauwenberghs, "A Comparative Study of Sound Localization Algorithms for Energy Aware Sensor Network Nodes," *IEEE Trans. Circuits Syst.*, vol. 51, no. 4, pp. 640–648, April 2004.

[15] V. Jungnickel, A. Forck, T. Haustein, U. Kruger, V. Pohl, and C. von Helmolt, "Electronic Tracking for Wireless Infrared Communications," *IEEE Trans. Wireless Commun.*, vol. 2, no. 5, pp. 989–999, Sept. 2003.

[16] P.J. McKerrow and S. min Zhu, "Modelling Multiple Reflection Paths in Ultrasonic Sensing," in *Proc. IEEE/RSJ IROS-1996*, vol. 1, pp. 284–291, Osaka, Japan, Nov. 1996.

[17] D. Niculescu and B. Nath, "Ad Hoc Positioning System (APS) using AoA," in *Proc. IEEE INFOCOM 2003*, vol. 22, no. 1, pp. 1734–1743, San Francisco, CA, April 2003.

[18] N.B. Priyantha, A. Chakraborty, and H. Padmanabhan, "The Cricket Location Support System," in *Proc. ACM MobiCom 2000*, pp. 32–43, Boston, MA, Aug. 2000.

[19] E. Sack, "Path Planning for Planar Articulated Robots using Configuration Spaces and Compliant Motion," *IEEE Trans. Robot. Automat.*, vol. 19, no. 3, pp. 381–390, June 2003.

[20] A. Savvides, C.-C. Han, and M. Srivastava, "Dynamic Fine-Grained Localization in Ad-Hoc Networks of Sensors," in *Proc. ACM MobiCom 2001*, pp. 166-179, Rome, Italy, July 2001.

[21] S. Suksakulchai, S. Thongchai, D.M. Wilkes, and K. Kawamura, "Mobile Robot Localization using an Electronic Compass for Corridor Environment," in *Proc. IEEE Int. Conf. Systems, Man and Cybernetics*, pp. 3354–3359, Nashville, TN, Oct. 2000.

[22] M. Sveda and R. Vrba, "Integrated Smart Sensor Networking Framework for Sensor-based Appliances," *IEEE Sensors J.*, vol. 3, no. 5, pp. 579–586, Oct. 2003.

[23] L.P. Tomas and A.W. Michael, "An Algorithm for Planning Collision-free Paths Among Polyhedral Obstacles," *Commun. ACM*, vol. 22, no. 10, Oct. 1979.

[24] B. Tovar, S.M. LaValle, and R. Murrieta, "Optimal Navigation and Object Finding without Geometric Maps or Localization," in *Proc. IEEE ICRA-2003*, vol. 1, pp. 464–470, Taipei, Taiwan, Sept. 2003.

[25] A. Zhu and S.X. Yang, "Path Planning of Multi-robot Systems with Cooperation," in *Proc. IEEE Int. Symp. CIRA-2003*, vol. 2, pp. 1028–1033, Kobe, Japan, July 2003.