



Development of Navigation Schemes for Grouped Mobile Robots Leading to Biomimetic Applications

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Abstract: Biomimetic autonomous group manipulation of mobile robots has great potential in artificial intelligence, smart life, and automation related applications. In addition, it is also possible to use it as a tool for exploring the behavior of biological group motion in groups such as geese and fish. In order to fulfill these goals, fundamental capabilities of identification, navigation, and communication between robots must be established. In this work, key schemes are proposed for carrying out subsequent navigation tasks. By integrating omni-wheel mobile robots with X-Bee communication protocols, Arduino controls, IR range finders, and CMOS cameras, as well as with wiimote multi-zone localization, tasks such as obstacle and collision avoidance, object following, autonomous movement, and the indoor localization of group robots are implemented as the first step toward the autonomous control of group robots for subsequent biomimetic and smart life applications. With the resolution of these key issues, more realistic scenarios can be designed to achieve real group robot applications for indoor service in the future.

Keywords: Mobile robots; obstacle avoidance; recognition; motion following; Autonomously Guided Motion Control; Arduino; X-Bee

I. Introduction

To understand and utilize the advantages of group movement and cooperation which occur in biological systems is a long term goal for researchers in many fields of study. In the robotics and artificial intelligence fields, the biomimetic control of robots has been conducted for years. For example, Xiao *et al* performed point to point (PTP) maneuvers of a robot-fish in a nonlinear and dynamically varied environment using fuzzy control as the key step toward the biomimetic control of a robot fish group [1]. On the other hand, by adapting the information processing rules used by living creatures such as paramecium to interpret environmental variables, Hirano *et al* [2] proposed a control scheme for mobile robots. They demonstrated that by creating coordinated

and cooperative relationships between large numbers of individual robots, complicated tasks can be fulfilled. In addition, through proper networking and communication, these robots can exchange their information and learn from their peers and from the environment, making it possible to tackle more difficult tasks which cannot be done by single or ungrouped robots. Consequently, it is possible to gain particular advantages by applying bio-inspired features into the group manipulation of mobile robots. As a result, several research laboratories have been deeply engaged in the study of the autonomous manipulation of robot groups for specific applications. These investigations have examined virtually all aspects of mobile robots including remote motion control, navigation, and speech recognition. For example, Fleischer proposed a biomimetic design for a cooperative mobile robot system designed to achieve a



foraging task [3]. Rooker and Birk [4] utilized wireless communications between two robots to establish environmental maps for robot manipulation. The ability to manipulate a robot group has enabled new applications in automatic indoor landscape arrangement, human machine interaction, and smart architectural technology. This work is inspired by the behavior of natural biological animal groups, in which the individual members could either access their own intelligence and information for performing motions and decision making or could exchange information in order to perform group motions and complete cooperative tasks. The bio-mimic approach could potentially lead to the large scale integration of robotic members to form massive groups for performing complicated tasks.

Navigation is a critical issue for biomimetic robot systems [5] to achieve accurate positioning by applying various transducers based on inertial force, ultrasonic transduction, imaging, or even the reception of radial signal strength indication (i.e., RSSI), or RFID [6]. Without a proper localization system, it is difficult to perform subsequent trajectory planning, task design, and feedback control. Once a sensory system is established, however, several key fundamental navigation challenges must also be met so that subsequent group robot manipulation, autonomous and group control, and task planning can be put into place, making it possible to accomplish a variety of biomimetic tasks. These tasks include collision avoidance, global localization schemes,

obstacles avoidance, and group manipulation. In order to perform these tasks, either the global positions of the robots must be captured by external sensors or the relative positions between robots must be provided by on-board transducers. For example, it is a common practice to utilize the information observed by external-mounted CCD cameras as the global positioning sensor for subsequent trajectory planning [7, 8] or by mounting on-board ultrasonic sensors for collision avoidance [9]. Both approaches have their own advantages and disadvantages for establishing the essential elements of a biomimetic environment. One advantage of the former approach is that it can obtain the global status of the robot group. It cannot, however, mimic the autonomous behavior of individual elements. On the other hand, the latter approach can provide information about individual robot decision making, but lacks the global coordination to perform tasks related to global positioning efficiently. As a result, we believe that it is critical to establish an environment which utilizes the advantages of both approaches, in order to produce subsequent mobile robot group biomimetic operations in indoor spaces. A typical schematic interaction relationship between robots, sensors, navigation, and wireless communications for building a smart living environment for intelligent life and for other bio-inspired applications is shown in Figure 1.

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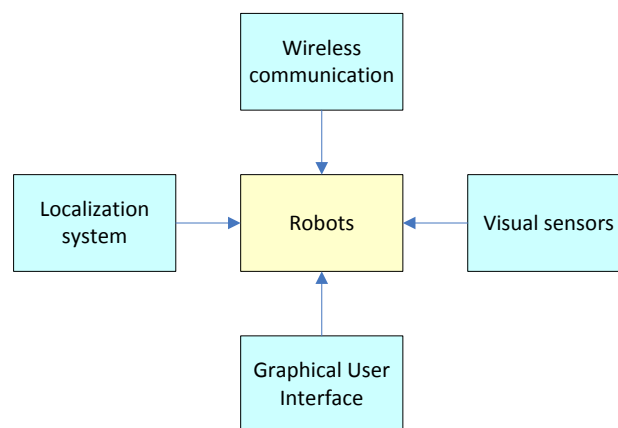


Figure 1. The typical schematic interaction relationship between robots, sensors, navigation, and wireless communications for establishing a smart living environment.

In this work, we combine both local and global approaches by utilizing a multi-zone wiimote localization technique developed by us [10, 11] for global information assessment and by utilizing IR range finders and CMOS cameras to provide the recognition of nearby objects which is necessary for decision making. Based on the global and local information obtained by these methods it is possible to propose novel solutions to the fundamental challenges involved in the development of



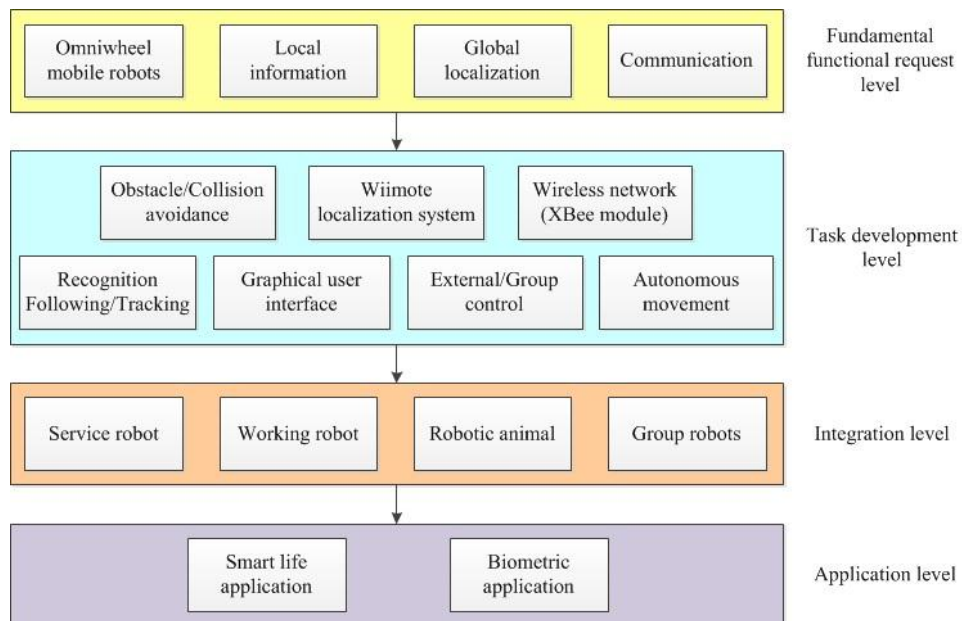


Figure 2. The research flow and the possible applications of the entire work.

effective robot navigation schemes. Finally, preliminary demonstrations of recognition, following [12], obstacle avoidance, and global positioning are presented to evaluate the feasibility of the concept. Through the improvement of essential elements in robot navigation, it is possible to demonstrate more dedicated group autonomous manipulations similar to that in the previous work [13] for smart live applications in the future. This paper is based on our preliminary work presented at the SICE 2011 conference [14], with more recent technical detail and an enhanced discussion.

The rest of this article presents the work in detail. In Section II, the overall system setup is established and introduced. Key schemes for specific approaches to navigation are addressed in detail in Section III, followed by an experimental demonstration in Section IV. The necessary discussion and comments regarding this study are addressed in Section V to highlight its importance, contribution, and perspective. Finally, Section VI concludes this research.

II. System Setup

As mentioned in Section I, the goal of this work focuses on controlling the interaction between individual mobile robots in an indoor living space for subsequent biomimetic and smart life applications. In order to achieve the goal a mobile robot group mounted with on-board sensors and communication and control systems is designed for investigating the fundamental navigation schemes required. In addition, a self-developed wiimote-based IR LED global localization technique is also adapted for precisely monitoring the global positions of these robots. Both internal and

external control environments are established by utilizing Arduino control cards and a NI LabVIEW system for processing the sensed information. The schematic plot for the entire system architecture is shown in Figure 2 and the key subsystems are addressed below.

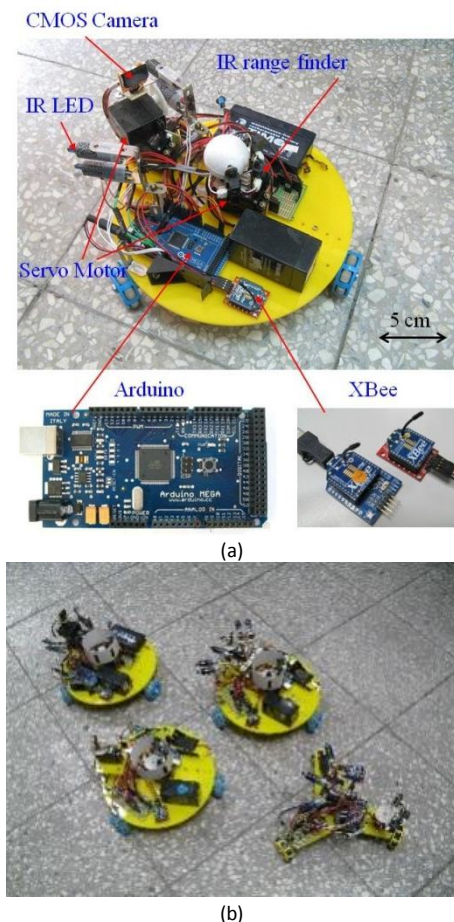


Figure 3. The self-built mobile robots. (a) Key components and (b) the fleet.

Mobile robot system:

Four omni-wheel type mobile robots designed and built by us are shown in Figure 3. Each omni-wheel is driven by three stepping motors (powered by a battery set) with an (UNO MEGA2560) Arduino control card equipped with a clock of 16 MHz and a (XBee® ZNet2.5) X-Bee communication protocol (based on IEEE 802.15.4 with a maximum data rate of 250 kpbs) for the basic motion and communication tool. The Arduino card sends PWM signals between 0 and 255 to control the wheel rotating speed (i.e., $\dot{\theta}$). As schematically shown in Figure 4, the global translating (\dot{x}, \dot{y}) and self-rotating velocities ($\dot{\phi}$) of those robots can be obtained by the following kinematics equation:

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\phi} \end{bmatrix} = \begin{bmatrix} -\frac{1}{R} & 0 & \frac{L}{R} \\ \frac{1}{2R} & \frac{\sqrt{3}}{2R} & \frac{L}{R} \\ \frac{1}{2R} & -\frac{\sqrt{3}}{2R} & \frac{L}{R} \end{bmatrix}^{-1} \begin{bmatrix} \dot{\theta}_1 \\ \dot{\theta}_2 \\ \dot{\theta}_3 \end{bmatrix}, \quad (1)$$

where R and L are the radii of the wheels and the robot, respectively. By Equation (1), the velocity and rotation, as well as the position and the orientation, of a robot can be determined by controlling the velocity of individual wheels. Furthermore, depending on the application, associated control laws to govern the relationship between the feedback information and the controlled $\dot{\theta}_i$ are also established for performing subsequent tasks.

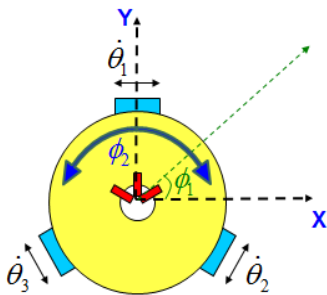


Figure 4. The schematic plot to illustrate the key parameters of omni-wheel robot motion.

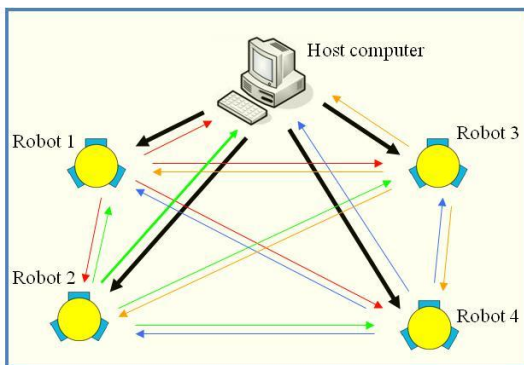


Figure 5. The schematic plot of mesh topology for robot communications.

Communication Network:

A wireless network between robots and their associated sensors is critical for group manipulation [15]. In this work, the communication is based on the X-Bee module mounted on board. In order to ensure the necessary quality of communication to cover all indoor mobile robots and to overcome possible signal attenuation and delay due to the presence of obstacles, a mesh topology (schematically shown in Figure 5) between the host and these robots is established by utilizing the X-Bee protocol. During experiments, the local host or the external supervisor sends string signals in a broadcasting manner. These string signals contain many data segments, which consist of an object-identified code followed by specific commands or data. The broadcasted signals are then received and decoded by each robot to recognize the specific parts which relate to that robot.

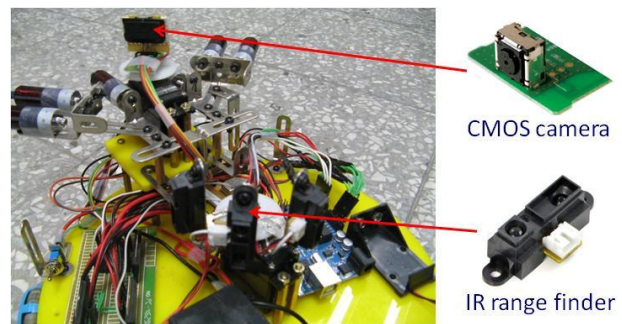


Figure 6. A picture to show the IR range finder for obstacle avoidance and the CMOS camera for object identification.

On-Board Obstacle Detection:

The ability to detect nearby objects is essential for mobile robot navigation. Unlike previous work using ultrasonic sensors, which cannot precisely determine the orientation of obstacles, in this work each robot is equipped with three sets of (Sharp GP2Y0A21) IR range finders shown in Figure 6 for detecting nearby objects and to perform obstacle avoidance. The effective detection range for these IR range finders is 10–80 cm. Since it is a light-of-sight based sensor, these range finders must be mounted on a scanner with a scanning angle of $\pm 120^\circ$ and a speed of 33.3 rpm in order to cover the desired sensing space. The major reason for choosing this three-sensor architecture is to increase the data update rate since the equivalent scanning speed is increased three fold in comparison with a single sensor approach.

On-Board Recognition:

In order to recognize and identify nearby mobile robots, auxiliary image sensors need to be incorporated. However, traditional cameras require extensive image processing and this could reduce the sampling rate and is also a challenge for on-board computational facilities. As a result, CMOS IR cameras used in Nintendo wiimote (also shown in Figure 6) are adapted in this work. Unlike other image sensors, CMOS IR cameras consolidate the information of an entire image to the positions of a few IR LEDs and the information of these coordinates can be directly accessible via NI LabVIEW. As a result, the subsequent data processing is easier and the system can have higher bandwidth. Based on these reasons, each mobile robot is equipped with an IR camera and different IR LED patterns for recognizing and being recognized. The effective sensing distance of those IR cameras is between 0.15 m and 5 m with a bandwidth of 107 Hz based on our previous characterization [11].

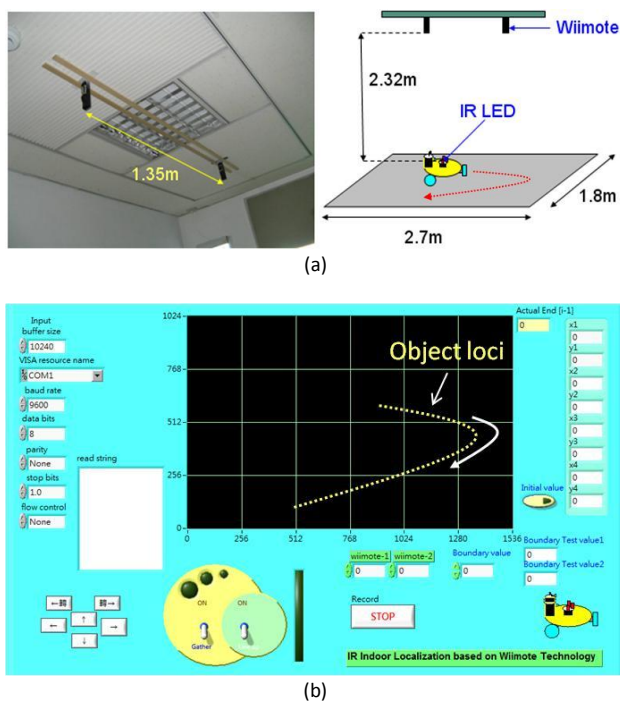


Figure 7. The wiimote global localization setup: (a) a picture and the schematic plot, (b) the corresponding data visualization interface written in LabVIEW.

Global Localization and External Supervision:

A wiimote array is installed on the ceiling (2.32 m above). Each mobile robot is equipped with an IR LED for localization. The locations of the captured IR LEDs are then transmitted to an external host computer via Bluetooth communication. Together with the multi-zone localization technique developed by us [11], this provides the global position information for the external

supervision of future task planning and control. Finally, the interaction between the robot group and the external human supervisor is established between the host computer and either the master robot (group mode) or all robots (individual mode) by using a graphic user interface written under a LabVIEW environment. The entire functional block diagram is shown in Figure 7.

III. Key Schemes Development

In order to perform navigation, two problems must be solved. First, a computational scheme for governing collision free interactions between a mobile robot and external obstacles or other mobile robots must be developed. Second, the ability of mobile robots to recognize and interact with each other must be established for subsequent group manipulation to take place since the ability to recognize and track a specific robot is a key for successful task planning in biomimetic motion control. Finally, it is also important to accurately localize the mobile robots with a sufficient bandwidth for external grouped control. In this work, three key schemes are developed to serve as the core for navigation and are addressed below.

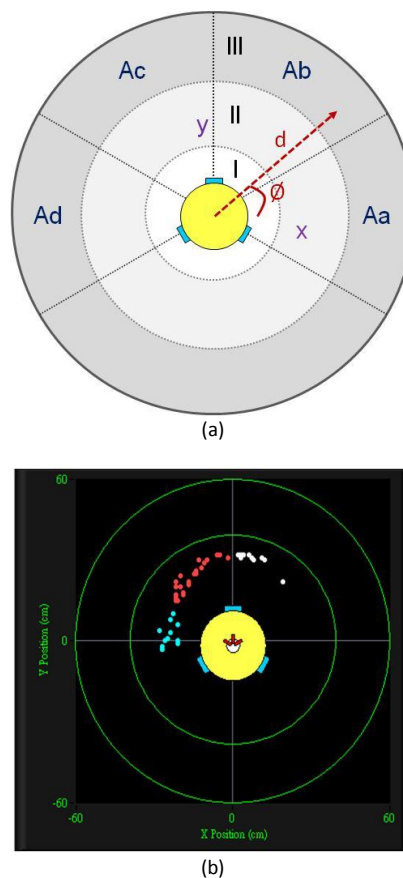


Figure 8. (a) Schematic plot for illustrating the sensing zones for obstacle avoidance and (b) a typical obstacle scanned data.

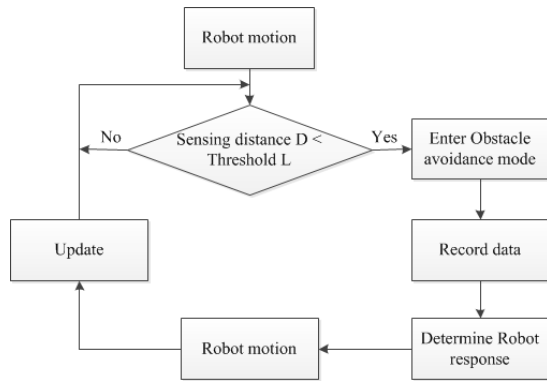


Figure 9. The flowchart of the obstacle avoidance scheme.

Obstacle Avoidance Scheme:

The schematic plot for illustrating the basic definition of a sensing zone is shown in Figure 8(a) and the scheme is briefly illustrated in Figure 9. Basically, using the measured azimuth angle of the motor rotation and the distance measured by the IR range finders, it is possible to establish a map and a corresponding decision process can be made (see Figure 8(b)). In this work, the azimuth angle and distance information of obstacles influence the orientation and the heading speed of the mobile robots, respectively. The range finder rotates with a speed of 33.3 rpm with a $\pm 120^\circ$ total scanned angle and is further divided into four azimuth zones (i.e., 60° for each zone). On the other hand, in radial direction we also assign two distance thresholds D and L for establishing a three influenced zone structure. As a result, there are in total 48 patterns representing the possible combinations of obstacle appearance patterns in azimuth direction. A look-up table listed in Table 1 is established to provide the corresponding motion commands. The robots are commanded to move forward initially (i.e., heading direction = 90°) at full speed if no obstacle is detected. If an obstacle is detected in a particular zone, the corresponding response is usually to command the robot to make a clockwise rotation. For obstacles sensed

at a distance greater than D , the situation is treated as obstacle-free and the original velocity is retained. On the other hand, if an obstacle is sensed at a distance of less than L , the obstacle is very close to the robot and certain emergency reactions must be performed. Finally, for an obstacle sensed at a distance between D and L , the robot will reduce its velocity and prepare to respond with the instructions provided by the look-up table. Using these approaches the courses of the robots are evaluated and updated after each motion step. It should be noted that it is possible to divide the total measurement area into more azimuth zones than those identified above, but with the disadvantage that a much more complicated look-up table for decision making is required and this issue can be further optimized in the near future. Previous work [9] used ultrasonic sensors for obstacle detection but they could not precisely determine the location of obstacles and the robots had difficulty making following up decisions. This approach, in contrast, can precisely determine the location of obstacles and promptly take appropriate steps in response.

Recognition and Following Scheme:

As mentioned earlier, each mobile robot is equipped with a set of IR LEDs and a CMOS IR camera, which is mounted on a servomotor with a scanning angle of $\pm 60^\circ$ and a resolution of 1024×768 for detecting the presence of nearby robots. By recognizing the image pattern of IR LEDs, each robot can distinguish its neighborhood. Also, by evaluating the coordinates of these LEDs, it is possible to calculate the relative distance and orientation between two robots and perform following motions. A *recognition and following* scheme is developed for searching out, recognizing, and tracking/following mobile robots by prompting the servomotor to rotate the CMOS camera.

Table 1. The look-up table for guiding the movement.

Azimuth zone		Obstacle appearance															
Ad			Y		Y			Y	Y			Y	Y	Y		Y	
Ac						Y	Y		Y				Y	Y	Y	Y	Y
Ab							Y	Y	Y	Y	Y	Y	Y		Y		
Aa		Y			Y	Y	Y				Y	Y	Y	Y			
I speed 50%	Heading direction(ϕ)	150°	30°	90°	90°	210°	210°	-30°	-30°	NA							
	CCW /CW	NA								CCW	CCW	CCW	CW	CW	CW	CW	CW
II speed 75%	Heading direction(ϕ)	90° (go ahead)															
III speed 100%	Heading direction(ϕ)	90° (go ahead)															

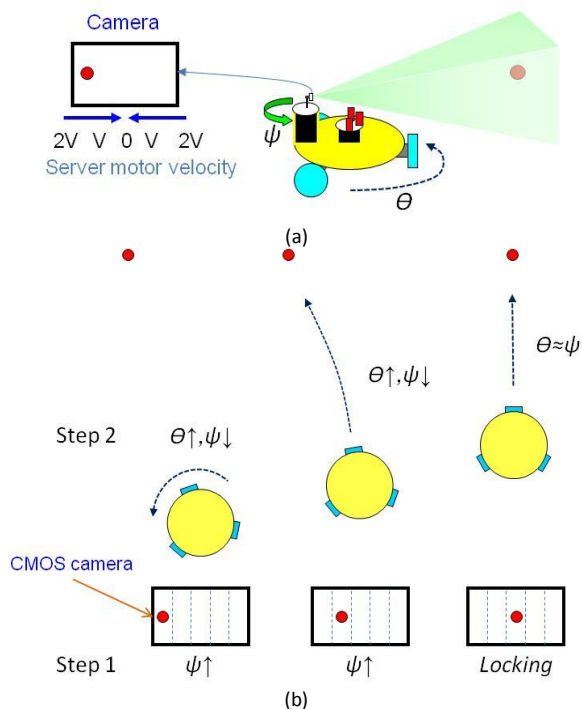


Figure 10. The schematic plot for illustrating the robot motion for object tracking: (a) robot and camera rotation for searching and (b) tracking the object.

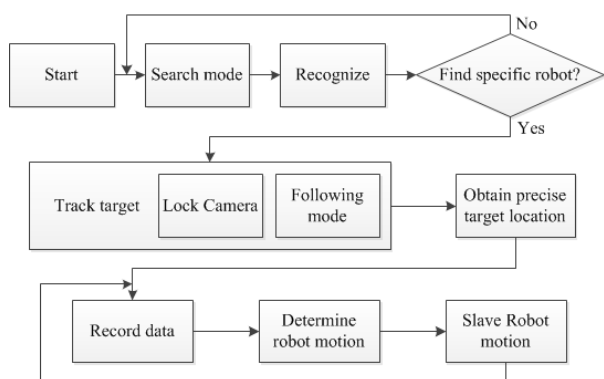


Figure 11. The flowchart for recognition and object following.

Alternatively, this scheme can be treated as a procedure to position the target robot at the center of the camera viewing window and can be further divided into two phases (i.e., the first phase for recognition and

the second phase for following). For the first phase, if the master robot cannot be found, the system will command the robot to perform a clockwise rotation and perform a scan again until the target can be seen by the CMOS camera.

This maneuver is schematically shown in Figure 10(a). Once the object is identified, the robot then adjusts its orientation and approaches the target as schematically shown in Figure 10(b). In order to perform an efficient computation, the visible area of the CMOS camera is divided into five zones for course control. Each zone is further divided into three zones and a look-up table (shown in Table 2) is also established to provide corresponding commands for robot manipulation. The goal of the first phase is to lock the target on the center line of the CMOS camera by adjusting the azimuth angles of the servomotor and adjusting the robot until the azimuth angle is in the vicinity of 0° (i.e., when pixels number between 384-640) with the robot directly facing the target. Once the target has been locked, the entire process is then switched to the second phase, which guides the robot to approach the target and keep the distance at a designated value. In this following mode the scanning range is significantly reduced, allowing more efficient tracking to take place. Technically, the recognition mode is equivalent to a procedure for horizontally moving the CMOS camera such that the target image approaches to the center line of the camera window. On the other hand, the following mode is to move the robot such that the target image can approach the center of the camera window in a vertical manner.

The flowchart of the entire process is shown in Figure 11. The entire process is somewhat analogous to sliding mode control, where the approach mode (bringing the system to the sliding surface) and the sliding mode (moving the system toward the final destination without leaving the sliding surface) can be equated to the search/recognition and the following modes shown in this work, although the physics and mathematics are different.

Table 2. Detail look-up table for object recognition and following operation.

Servo-motor Tracking / CMOS camera	4~344 (pixel)		344~384 (pixel)		384~640 (pixel)			640~680 (pixel)		680~1020 (pixel)					
Responding	Angle-2°		Angle-1°		Locking			Angle+1°		Angle+2°					
Omni robot / CMOS camera	q1 4~256 (pixel)		q2 256~384 (pixel)		q3 384~640 (pixel)			q4 640~768 (pixel)		q5 768~1020 (pixel)					
Servo-motor angle	90° ~ 150°	90°	30° ~ 90°	90° ~ 150°	90° ~ 90°	30° ~ 90°	105° ~ 150°	75° ~ 105°	30° ~ 75°	90° ~ 150°	30° ~ 90°	90° ~ 150°	90° ~ 90°	30° ~ 90°	
Responding (Motion & Heading)	L-A	∅=90°	CW	L-A	∅=90°	R-B	CC W	∅=90°	CW	L-B	∅=90°	R-A	CC W	∅=90°	R-A

L-A = left parabolic path, L-B = left arc path, R-A = right parabolic path, R-B = right arc path



Wiimote Global Localization Scheme:

In our previous work, the horizontal travel distance between a wiimote and an IR LED has been calibrated and a 2D multi-zone localization scheme has been developed to cover the entire indoor space. In this work, we adapt this established technique [11] as the global localization scheme. However, unlike the previous work [11], which deployed an IR array on the ceiling and mounted a wiimote over a robot, they are interchanged in this work due to limited available space on a robot. As already shown in Figure 7, two wiimotes are deployed on the ceiling to cover a sensing area of 1.8x2.7 m² with a spatial resolution of 1.75 mm for monitoring the motion, which is sufficient for the purpose of demonstration. In addition to this original purpose, it was immediately realized that by properly utilizing the obtained global position information, it is possible to perform more sophisticated applications such as precision positioning of an entire robot group or, in the future, creating interactions between two independent groups of autonomous robots. However, the current approach requires even more wiimotes in order to extend the sensing area to equal typical indoor space and is therefore a costly solution. In addition, the scheme proposed in [11] cannot count rigid body rotation. A modified wiimote localization scheme is developed and validated by us in [16, 17]. In that scheme, at least two IR LEDs must be simultaneously observed in order to reveal rigid body rotation and to obtain the rotation angle. Once the rotation angle is obtained, a coordinate transformation is performed to convert the current camera coordinate into a modified camera coordinate, which is parallel to the global coordinate. Under such a circumstance, the displacement can be accumulated to update the position. This modified scheme will be incorporated into future work.

The three schemes mentioned above serve as the core for key navigation tasks such as obstacle avoidance during movement, individual robot navigation and interaction, and group manipulation. All of these are implemented and tested in Section IV to serve as the foundation for biomimetic group robot manipulation.

IV. Experimental Results

In this section, various fundamental benchmark problems in navigation are experimentally demonstrated to allow us to evaluate overall performance and to examine possible faults in recognition and communication between objects, as well as to refine the manipulation schemes. The performance measured and lessons learned could be very valuable in the future for large scale integration in biomimetic and smart building related applications. These demonstrations are listed in a brief summary in Table 3 and the detailed results are presented below.

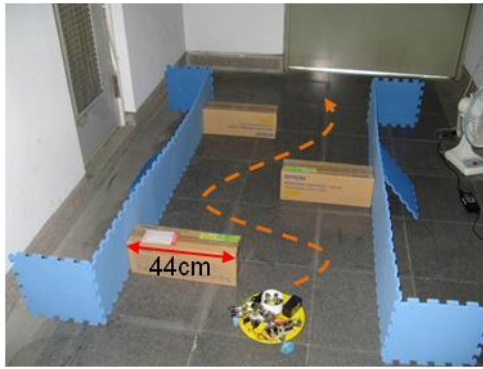
Obstacle avoidance:

As shown in Figure 12(a) and (b), a maze-like passage is designed to test the performance of obstacle avoidance. A robot is commanded to walk through the passage within 10 seconds without colliding with the walls. In addition a path with a dead end is also used and the results shown in Figure 13 indicate that the robot can successfully walk out from it in a reasonable amount of time without getting trapped inside. These features are important for indoor service robots since inside a typical living space passages could be complicated and include many dead ends. Robots without the above mentioned abilities would be impractical for use in indoor service applications.

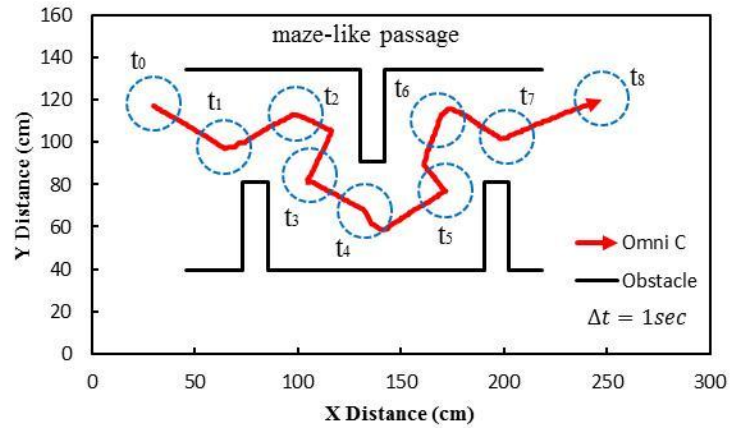
Table 3. Brief description on experimental demonstration.

Test Item	Hardware	Scheme Used	Scenario Summary
Obstacle avoidance	One robot, IR range finders	A	Demonstration for entering and leaving maze-passage and a dead-end
Collision avoidance	Two robots, IR range finders	A	Collision avoidance of two mobile robots
Following	Two robots, IR range finders, CMOS camera	A+B	Recognition and following between a master and a slave robots
External group control	Three robots, IR range finders, CMOS cameras, IR LEDs	A+B	Motion of three robots subjects to external control
Group autonomously movement	Four robots, IR range finders, CMOS cameras	1. A 2. A+B 3. A+B+C	1. Collision-free movement 2. Gathering motion 3. Master-slave recognition and following motion

A: Obstacle avoidance, B: Recognition / following, C: Autonomous movement

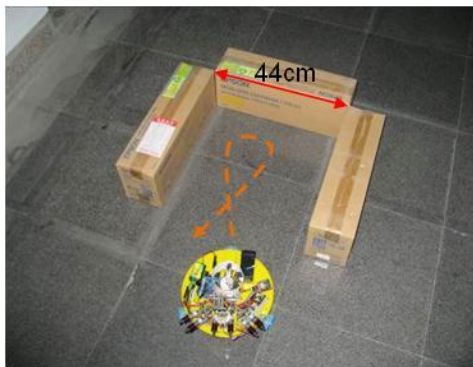


(a)

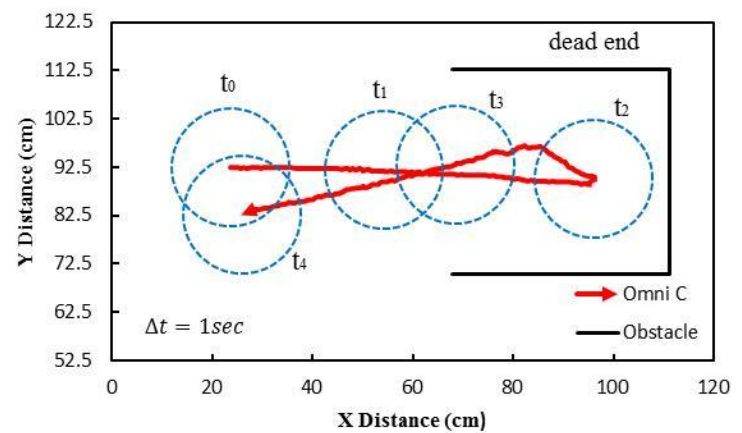


(b)

Figure 12. The maze-passage demonstration for obstacle avoidance.

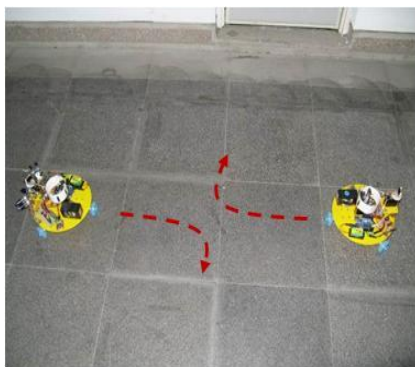


(a)

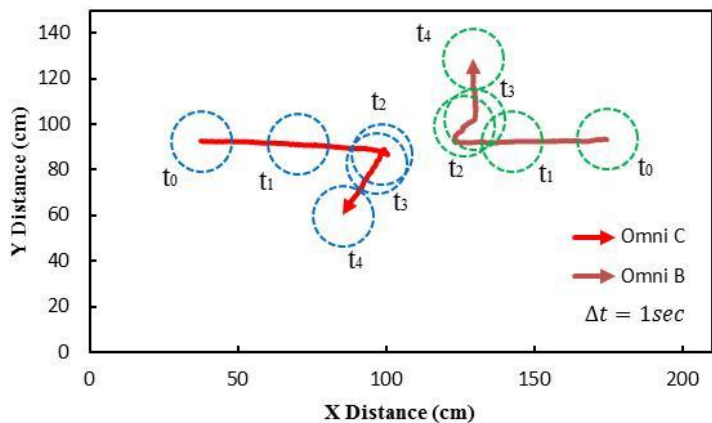


(b)

Figure 13. The demonstration for entering and leaving a dead-end.



(a)



(b)

Figure 14. The collision avoidance of two mobile robots.

Collision avoidance between two robots:

In a multi-robot workspace, collisions between two or more robots must be prohibited and this issue is investigated here. This can be treated as a dynamic situation of the obstacle avoidance problem previously

described. As shown in Figure 14, two mobile robots approach each other. Once the relative distance is within the threshold, both robots will make decisions to avoid collisions based on the obstacle avoidance scheme addressed above.

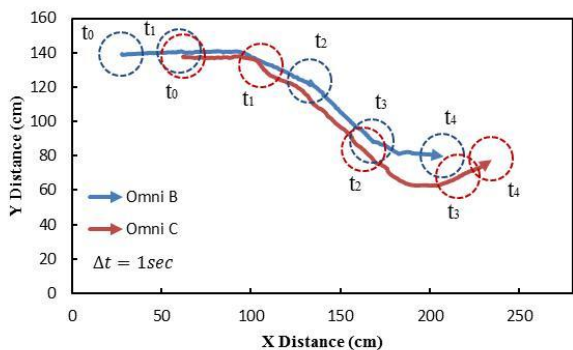


Figure 15. The recognition and following between a master and a slave robots.

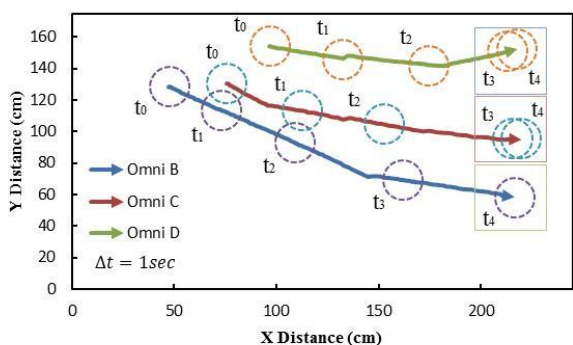


Figure 16. Motion of three robots subjects to external group manipulation.

Following:

The ability of slave robots to follow a master robot is a technical capability which is fundamentally necessary for the subsequent realization of autonomous motion control of robot groups. Figure 15 demonstrates the results of our scheme in robot following. The master robot performs a general planar motion and is followed by a slave robot. As one can see, the slave robot follows the path of the master robot very well.

External control and autonomous group movement:

A well-established communication network is the key to the successful manipulation of robot groups. This can be divided into two categories. The first category concerns the interaction between the host and individual robots (i.e., external control) and the established X-Bee protocol allows the host computer to send signals in a broadcasting manner to all robots. These robots then decode the data to extract their own unique motion commands which are subsequently used to drive their servomotors to achieve the specified goal. By this approach and through careful motion planning, an external hosted group motion can be achieved. On the other hand, by mimicking animal group motion behavior, the second category deals with autonomous group

movement. In that task, one robot is assigned as the master and the rest are slaves. The master either receives a command from the host computer or forms its own decision to plan a motion based on sensed information. The slave robots then move with the master robot to form specific motion patterns. Through such an approach, an autonomously guided robot group motion can be realized.

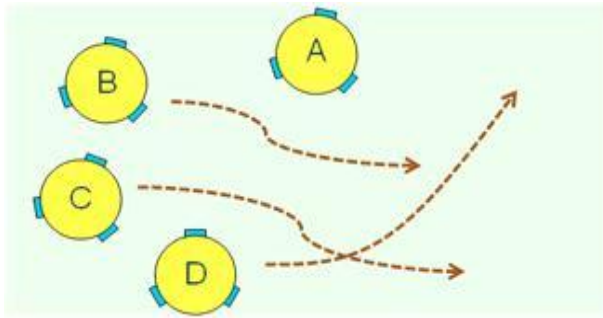
To demonstrate the external control task the host broadcasts a message to all three mobile robots and asks them to move toward their corresponding destinations. The results are successfully shown in Figure 16 and the results indicate that it is possible to control a large number of robots simultaneously to carry out real applications (such as smart building elements) by just sending an information package while the bandwidth can still be maintained. This could be very useful for smart building applications where a large number of building elements must be moved to specific locations in order to fulfill certain functional requirements.

Finally, autonomous movement experiments are performed based on the technical capabilities established above. Our four mobile robots are designed to perform three tasks. First, we allow these four robots to move freely without colliding in the workspace as shown in Figure 17(a), (b). Next, as shown in Figure 17(c), (d), with one robot serving as the master, all other slave robots move toward the master once they are asked. Finally, these slave robots follow the master to form a following motion without colliding as shown in Figure 17(e), (f). These successful demonstrations will make it possible for us to investigate more realistic situations in the future with the aim of achieving real group robot applications for indoor service.

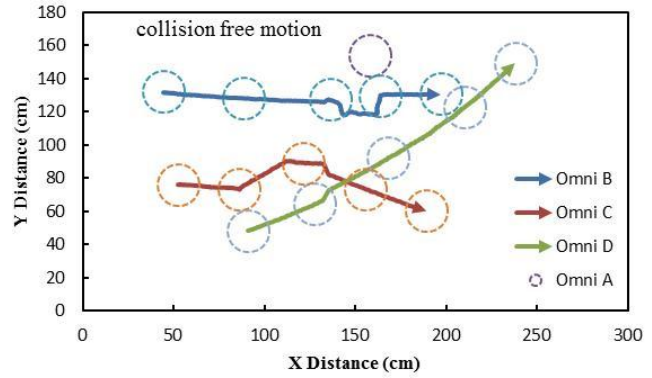
V. Discussion

In this work, the fundamental navigation issues involved in the bio-inspired group manipulation of mobile robots are investigated. Several schemes are developed for the first time to serve as the core for these navigation tasks. These schemes include obstacle avoidance, robot tracking and following, and global localization. Experimental studies are subsequently performed to successfully demonstrate the effectiveness of these schemes in the creation of autonomous group motion. With the establishment of these navigation capabilities, it is possible to generate more realistic scenarios for the biomimetic control of group mobile robots in indoor smart living applications.

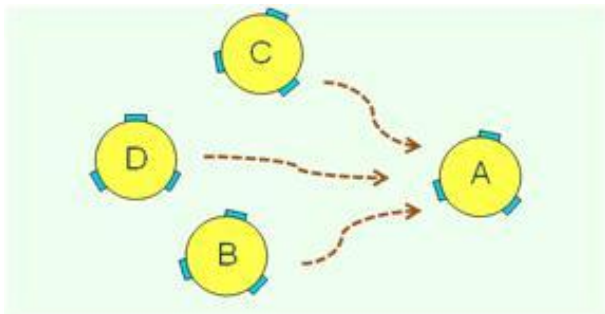
In this work, IR-based range finders can accurately measure the distance of obstacles. This is a major advantage in comparison with other sensors such as



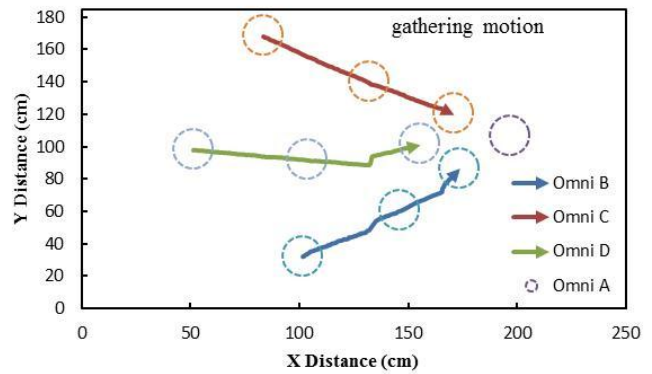
(a)



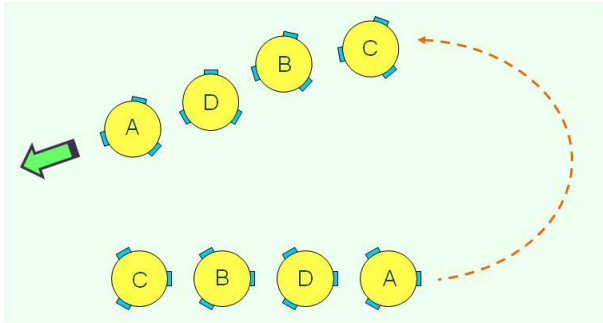
(b)



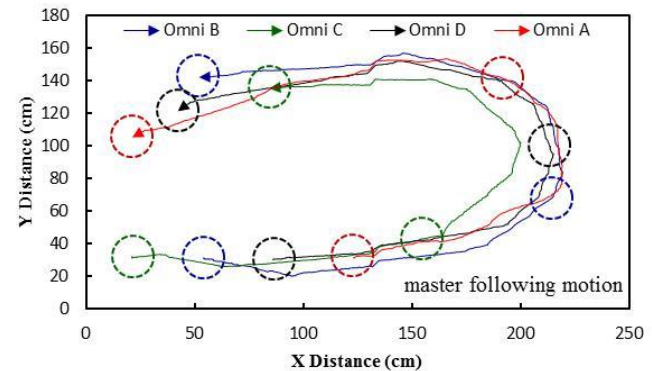
(c)



(d)



(e)



(f)

Figure 17. Autonomously group movement demonstrations: (a) and (b) collision-free movement; (c) and (d) gathering motion; (e) and (f) master-slave recognition and following motion between four robots.

ultrasonic obstacle detectors. However, their very narrow viewing angle also implies that they cannot work properly without a properly designed scheme in which they collaborate with a scanning mechanism. This work demonstrates such a prototype and validates the feasibility of the proposed mechanism and scheme. The current scheme uses a finite state approach to build a look-up table for mapping motion commands to their corresponding sensed state, which can be further optimized. For example, it is possible to define an obstacle threat probability (which is a function of

obstacle size and distance) as a performance index and then define the corresponding robot motion to minimize the threat probability. By such an optimal control approach, we believe performance can be further improved and consequently this approach has become central to our current work.

In addition, by utilizing the advantages of the wiimote CMOS cameras, target identification can be realized by evaluating the pattern formed by a few IR LEDs. In comparison with other image identification methods, this approach requires less computational time



and the effective bandwidth can be improved. Furthermore, object tracking and following can also be easily achieved by simply monitoring the location of a particular set of IR LEDs. By using the current scheme which is similar to a "sliding control" approach, it is possible to successfully track a target and perform object following movements. Due to limitations in hardware performance, the scheme is currently implemented in a look-up table manner. In the future, by improving the response rate and resolution of mobile robots, the current approach can be replaced by an associated control law and the performance can be further optimized.

The current wiimote global localization scheme can allow us to determine the global coordinates of mobile robots by using multiple wiimotes. In our previous scheme, this could not be achieved without the information of the coordinates of the starting location. The current approach (i.e., multiple wiimotes and a single IR LED), however, is much more expensive than the previous approach (which included a single wiimote and an IR LED array) and this would be a serious concern for entire indoor space localization since it would require many wiimotes. As a result, we are currently re-investigating the previous wiimote scheme by alternating the pattern of IR LED arrays in such a way that the requirement of initial position information can be removed. Through this new approach, a low cost and accurate indoor global localization scheme can be realized.

The experimental studies described in this paper demonstrate the feasibilities of our mobile robots in performing key navigation tasks which are essential for carrying out biomimetic maneuvers with mobile robot groups. In the future it may be possible to utilize the group manipulation of mobile robots to realize specific functional requirements for smart living applications, providing we have the proper scenario designs. We may yet see mobile chairs line themselves up and arrange themselves autonomously in exhibition halls [18].

VI. Summary and Conclusion

The autonomous control of a group of mobile robots has fundamental importance for bio-mimic or smart living space related applications. In addition, it also provides a technical platform for studying the behavior of grouped animal motion for biomimetic engineering. However, several fundamental concerns in communication, coordination, obstacle avoidance, and cooperation must be solved and demonstrated before detailed task planning can be realized. In this work, which is based on wiimote CMOS cameras and IR range

finders, we propose three schemes which can serve as core components in a solution designed to meet these concerns. These schemes are obstacle avoidance, target recognition and tracking/ following, and global localization. Both hardware design and software implementation schemes are developed in order to establish the necessary capabilities to make the autonomous control of mobile robots possible. Essential preliminary demonstrations are performed to evaluate the effectiveness of the proposed scheme and to elucidate the potential applications of this work. In the future, it is expected that more sophisticated schemes such as the interaction between two autonomously controlled robot groups can be developed for indoor service applications. Now that these key issues have been solved, more realistic scenarios can be designed for biomimetic studies in the future to achieve real group robot applications in indoor smart living technology or even in grouped animal behavior.

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References

- [1] Q. Xiao, F. Kong, and J. Tao, "Research on point-to-point of biomimetic robot-fish based on fuzzy control," in *International Conference on Electric Information and Control Engineering*, Wuhan, China, 2011, pp. 1652-1655.
doi: [10.1109/ICEICE.2011.5777749](https://doi.org/10.1109/ICEICE.2011.5777749)
- [2] A. Hirano, T. Tsuji, N. Takiguchi, and H. Ohtake, "Biomimetic control of mobile robots based on the information processing model of paramecium," in *The Eleventh international Symposium on Artificial Life and Robotics*, Oita, Japan, 2006, pp. 313-318.
Available:
http://www.bsys.hiroshima-u.ac.jp/pub/pdf/C/C_14_3.pdf
- [3] J. G. Fleischer, "A method for biomimetic design of a cooperative mobile robot system to accomplish a foraging task," M.S. Thesis, Department of Mechanical Engineering, Colorado State University, Fort Collins, Colorado, US, 1999.
- [4] M. N. Rooker and A. Birk, "Multi-robot exploration under the constraints of wireless networking," *Control Engineering Practice*, vol. 15, no. 4, pp. 435-445, 2007.
doi: [10.1016/j.conengprac.2006.08.007](https://doi.org/10.1016/j.conengprac.2006.08.007)



- [5] M. O. Franz and H. A. Mallot, "Biomimetic robot navigation," *Robotics and Autonomous Systems*, vol. 30, no. 1–2, pp. 133-153, 2000.
doi: [10.1016/S0921-8890\(99\)00069-X](https://doi.org/10.1016/S0921-8890(99)00069-X)
- [6] G. Zecca, P. Couderc, M. Banatre, and R. Beraldi, "Swarm robot synchronization using RFID tags," in *IEEE International Conference on Pervasive Computing and Communications*, Galveston, TX, 2009, pp. 1-4.
doi: [10.1109/PERCOM.2009.4912788](https://doi.org/10.1109/PERCOM.2009.4912788)
- [7] C. L. Hwang and L. J. Chang, "Trajectory tracking and obstacle avoidance of car-like mobile robots in an intelligent space using mixed H_2/H_∞ decentralized control," *IEEE/ASME Transactions on Mechatronics*, vol. 12, no. 3, pp. 345-352, 2007.
doi: [10.1109/TMECH.2007.897281](https://doi.org/10.1109/TMECH.2007.897281)
- [8] A. H. Pratomo, A. S. Prabuwo, M. S. Zakaria, K. Omar, M. J. Nordin, S. Sahran, S. N. H. S. Abdullah, and A. Heryanto, "Position and obstacle avoidance algorithm in robot soccer," *Journal of Computer Science*, vol. 6, no. 2, pp. 173-179, 2010
- [9] Y. S. Chen and J. Jih-Gau, "Intelligent obstacle avoidance control strategy for wheeled mobile robot," in *ICROS-SICE International Joint Conference*, Fukuoka, Japan, 2009, pp. 3199-3204.
Available:
http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5334116&tag=1
- [10] P. W. Chen, K. S. Ou, and K. S. Chen, "IR indoor localization and wireless transmission for motion control in smart building applications based on wiimote technology," in *SICE Annual Conference*, Taipei, Taiwan, 2010, pp. 1781-1785.
Available:
http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5602939
- [11] P. W. Chen, "IR indoor localization and wireless transmission for motion control in robotic architecture and intelligent life applications based on wiimote technology," M.S. Thesis, Institute of Nano Science and Microsystem Engineering, National Cheng-Kung University, Taiwan, 2009.
- [12] B. S. Choi, J. W. Lee, and J. J. Lee, "Target-following scheme for mobile robots based on the virtual sub-goal points," *Information — An International Interdisciplinary Journal*, vol. 13, no. 6, 2010
- [13] H. Yonghui, W. Zhao, L. Wang, and Y. Jia, "Underwater target following with a vision-based autonomous robotic fish," in *American Control Conference*, St. Louis, MO, 2009, pp. 5265-5270
- [14] M. H. Chen, D. Gu, Y. D. Fu, C. H. Pi, K. S. Ou, and K. S. Chen, "Wireless group manipulation of autonomously guided mobile robots for smart living space applications," in *SICE Annual Conference*, Tokyo, Japan, 2011, pp. 2143-2148
- [15] W. Li and W. Shen, "Swarm behavior control of mobile multi-robots with wireless sensor networks," *Journal of Network and Computer Applications*, vol. 34, no. 4, pp. 1398-1407, 2011.
doi: [10.1016/j.jnca.2011.03.023](https://doi.org/10.1016/j.jnca.2011.03.023)
- [16] D. Gu, "Development of wiimote indoor localization technology and omni-directional vehicle trajectory control for intelligent life applications," M.S. Thesis, Department of Mechanical Engineering, National Cheng-Kung University, Taiwan, 2011.
- [17] D. Gu, P. W. Chen, K. S. Ou, Y. D. Fu, and K. S. Chen, "Design and performance evaluation of wiimote-based two-dimensional indoor localization systems," presented at the 11th International Conference on Automation Technology, Taiwan, 2011.
- [18] InfoJelte at YouTube, *Take a seat*, YouTube, 2007, [Online].
Available:
<http://www.youtube.com/watch?v=2Dgaz6NIUFk>

