Cooperative Overhead Transportation of a Box by Decentralized Mobile Robots

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***Abstract*— We demonstrated that the regular behavior-based architecture can be used to control decentralized multiple robots on a tightly-coupled task. With carefully designed behaviors, the robots can work cooperatively and effectively. We divided the behaviors into two types: individual behaviors and group behaviors. Group behaviors, embedded as layers in the behavior-based architecture, act as a mechanism to induce coordination and synchronization among robots. The tightly-coupled task that we use as our testbed is the cooperative overhead transportation of a box, in which two robots have to carry a box over their tops. Little movement error will result in a fall of the box. The result illustrated the validity of the proposed method. The robots can move the box to a goal without falling down with a success rate of 80%.**

***Keywords*—cooperative robotics, decentralized robots**

I. INTRODUCTION

Presently, the control of multiple mobile robot groups is divided into two types: centralized control and decentralized control. In centralized control, the system's operation depends entirely on a central unit, which makes the system susceptible to failure of the central unit. Decentralized control, on the other hand, are robust and scalable. The decentralized control has been developed for the use in a lot of loosely-coupled tasks such as multiple robot box-pushing, formation control, and transportation, etc. However, there are not many examples of tightly-coupled tasks with decentralized control. Tightly-couple tasks are tasks that need closed coordination of robots' actions in order to achieve a goal. The main reason is that tightly-coupled tasks require close and precise synchronization, which is a weak point of the decentralized control. In this paper, we demonstrate that the use of behavior-based approach with some synchronization can handle a tightly-coupled task pretty well. In our experiment, we used the cooperative overhead transportation problem as a tested. In this problem, two mobile robots have to carry and maintain a box over their body (see Figure 2) while moving to a desired position. This problem is a tightly couple task because it requires both robots to keep the box on top of them for all time. A little error will make the box to fall down and fails the task.

In cooperative multiple mobile robot research, there are many techniques proposed to make robots work together. The behavior-based control for multiple mobile robots was proposed according to the idea of collective robotics from social insect, and applied to multiple mobile robots box-pushing. Then, researchers developed an arbitration unit by using an adaptive logic network (ALN) [1][2]. Moreover, the novel action selection method for multiple mobile robots box-pushing in a dynamic environment was presented [3]. In addition, the decentralized control algorithm for transportation of a single object by multiple non-holonomic mobile robots was introduced. They extended the leader-follower type control algorithm, which was originally used in holonomic robots to be used with non-holonomic mobile robots by attaching a passive sliding mechanism to each follower [4]. Furthermore, the decentralized control algorithm of multiple mobile robots transporting a single object in coordination was proposed in identical work. In this algorithm, each robot was controlled as if it had a caster-like mechanism and transportation of a single object by multiple mobile robots without using the geometric relationship among robots [5].

Normally, the control architecture of the transportation problem utilizes the "leader-follower" mechanism. This method is similar to semi-centralized control because a group decision depended on the leader agent. This method is not robust, because the follower agent cannot continue working when the leader agent stops its operation.

This paper investigates the decentralized control mechanism which can solve the robustness problem in the leader-follower method used in coordinating multiple mobile robots. This study proposed a mechanism for the application of decentralized mobile robots in cooperative overhead box transportation.

II. MECHANICAL DESIGN CONCEPTS

We focus our study on the decentralized control of multiple mobile robots. These robots perform cooperative overhead transportation of a box. Each mobile robot is driven by two wheels actuated independently. We assume that both mobile robots carry an object coordinately in that they need to keep a fixed distance between them while moving around. Since the robot could not move along the direction of the wheel axis, we need a mechanism to handle the motion conflicts between the robots along their wheel axis.

In order to maintain a fix distance while moving forward, the robots must have a local feedback of their movements. We utilize a free rotational joint plate, which is located at the top of the robot's center, as shown in Figure 1. The joint is mounted with an optical encoder to measure the displacement angle caused by misalignment of the box. Moreover, the top plate is equipped with an infrared sensor used to detect whether the box is in place or likely to fall off (see Figure 3). In Figure 4, the left picture shows both robots are in place but the right robot has error in its direction. At this situation, if both robots continue to move forward, the box will move to the edge of the right robot and fall down. Before falling down, the infrared sensor will detect this event, and the robot should try to slide itself back under the box.

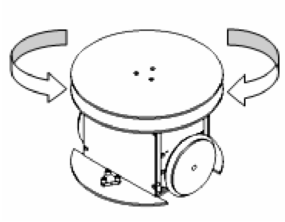

Figure1. Free rotation point with a top plate.

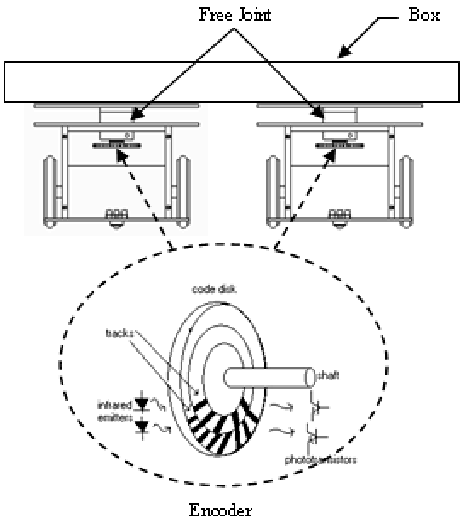

Figure2. Encoder sensor attached to the free rotational joint.

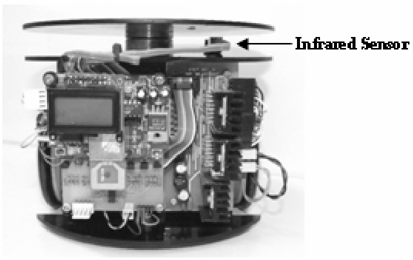

Figure3. Real robot: each of the robots is equipped with an object infrared sensor, a free rotational joint and a free joint encoder sensor.

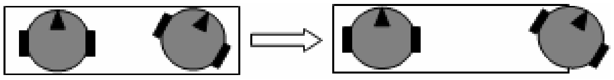

Figure4. Situation when the mobile robots have unsynchronized movement.

III. SYSTEM ARCHITECTURE

A. Movement Design

1) Move straight forward: Both robots will move forward when the box is safe from falling down and the free rotational joint does not deviate from the robot's forward direction.

2) Turn: The box can be turned left or right by letting the left or right-side robot move forward as usual, while the other robot stays still and maintains the heading reference to the box. This will make one robot acts as a rotation point and the other rotate in circular motion around that point (see Figure 5).

3) Passing through a narrow passage: The robots can move pass through a narrow passage by letting the short side of the box face the front. This is accomplished by making both robots change their formation from horizontal to vertical forward direction. The robots act similar to the "turn" movement, but the robot that is a point of rotation will not rotate with the movement of the box. In addition, the other robot that move forward will turn around 90 degree backward after it reach the desired point (see Figure 6).

4) Switching roles: The robots swap their position between left and right. This behavior is used in some situations when the box has to be carried along a narrow passage. (see Figure7).

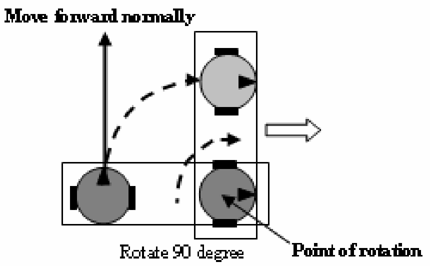

Figure5. The robots turn right.

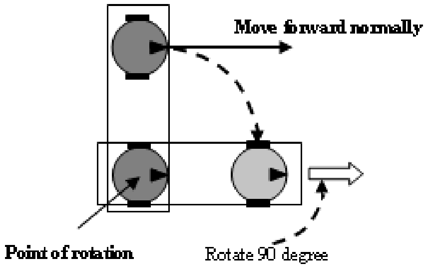

Figure6. The robots change their formation.

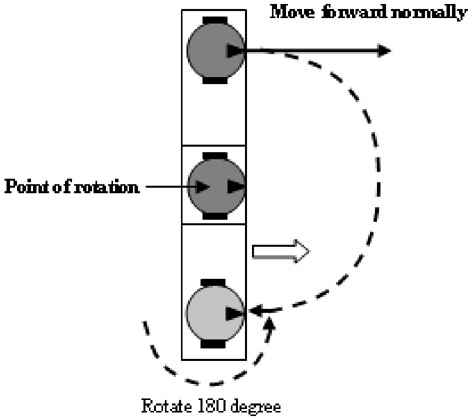

Figure7. The robots switch roles.

B. *Control Architecture*

Robot control architecture can be divided into two parts: individual architecture, which controls each robot's behavior and group architecture, which controls the direction of the robot group. In individual architecture, we applied a behavior-based approach to control each mobile robot. In group architecture, we used decentralized control embedded in the behavior-based hierarchy for control robot cooperation.

C. *Robot Behavior Design*

We designed the behaviors of two robots based on the requirements of the task according to individual behaviors and group behaviors. Then, we prioritize these behaviors respectively to the level control and embed them into the subsumption structure [6]. The diagram of our system is shown in Figure 4, in which there are two types of behaviors: individual behaviors and group behaviors. Since we use the subsumption architecture which only allows individual behavior, the group behavior, which controls coordination of the robots are created virtually as layers in the subsumption architecture as are linked together by a communication channel.

1) Individual Behaviors: Individual behaviors are basic behaviors for controlling movements of each robot. The details for each behavior are as follows.

a) Keep the box on the top: The robots must carry the box over its top plate. This behavior is activated when the box slid off the plate due to errors from the wheel encoders. This prevents the infrared sensor from sensing the box. After that the robot stops and sends a message "not ready" to command other robots to stop moving and wait until they receive the "ready" message. Then, the robot rotates approximately 90° and moves forward in order to push the box back in place at the top of its center and makes the infrared sensor detect the box again. Finally, the robot turns back to its previous forward direction and sends "ready" message to other robots.

b) Move forward: The robot will move forward when the box is safe from falling down. The safe situation is defined as follows. The infrared object sensor senses the box on robot's top plate. The free rotational joint does not rotate off the robot's forward direction. And, the robot receives a message "ready" from the other robot.

c) Keep straight direction: When the free rotational joint encoder detects its displacement, the robot's heading is not parallel to its peer. This happens from accumulated wheel encoder errors while moving. This makes the robots divert away from each other. If the heading error is detected, the mobile robots will turn back in the opposite direction detected from the free rotational joint encoder to restore its original heading.

2) Group Behaviors: To achieve cooperative task, some coordinating behaviors between robots are necessary. The behaviors used in the overhead box transportation task are designed as follows.

a) Forward synchronization: This behavior is used to maintain the robots' synchronized movement to prevent the box to fall off. This is to make sure that the box can be moved forward only when both robots are ready. The robots uses a communication channel for sending a message "ready" or "not ready" to another robot to be a signal for moving forward together.

b) Turn synchronization: The box can be turned left by letting the right-side robot move forward as usual while the left-side robot stays still while maintaining the heading reference to the box. This will make one robot acts as a rotation point and the other rotates in circular motion around that point. The same principle can be applied for right turn. The turn synchronization behavior is the behavior for the robot to stays in order to achieve turning action. This behavior is activated when the robots want to turn left or right. The behavior will run for a fix amount of time according to the required angle of turn.

c) Passing through a narrow passage: Since the box is moved forward horizontally, it cannot move forward passing through a narrow path. This behavior makes both robots to change their formation from horizontal to vertical forward direction. This behavior is activated until the box has been moved pass the narrow passage. After that, the robots change their status back to their original state.

d) Roles interchange: This behavior is activated when the robots want to swap their position between left and right. This behavior is useful when the box has to be carried along some special narrow passages where the robots need to swap their position in order to move pass them. When this behavior is activated, the robots act similar to the "passing a narrow passage" behavior. Only when getting back to the original state the robots change their internal state from left to right and right to left accordingly.

3) Layers of Control: In the original subsumption architecture, input signals are only from sensors and the behaviors are activated only by those signals which are stimulations coming from the environment. In this research, we used a subsumption architecture that does not have only inputs from sensors but also inputs from messages among robots in the group. Layer of control for each robot on the cooperative overhead transportation task, is shown in Figure 9. This layer of control consists of both individual and group behaviors.

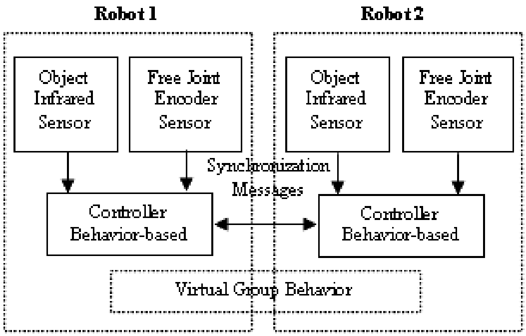

Figure8. System architecture

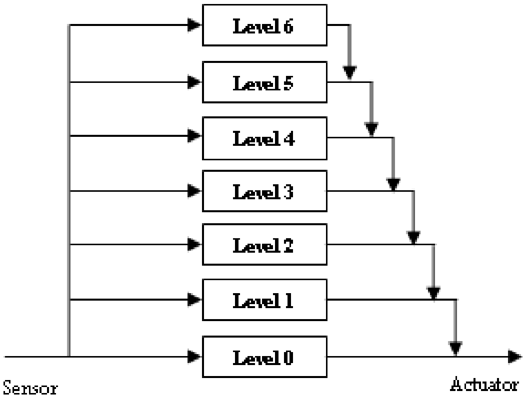

Figure9. Layers of Control in the subsumption architecture

- Level 0: Keep the box on the top.
- Level 1: Forward behavior (Group behavior).
- Level 2: Move forward.
- Level 3: Turn behavior.
- Level 4: Turn behavior (Group behavior).
- Level 5: Passing a narrow passage (Group behavior).
- Level 6: Roles interchange (Group behavior).

IV. VERIFICATION BY SIMULATION APPROACH

Before experimenting real robots, we verified the control mechanism of our robots with a simulation program. This program was developed based on multithread structure. The robots and the environment run on separate threads in order to emulate asynchronous environment in the real world. The simulated environment utilizes forces and frictions equations to describe the box's movement. In our experiment, we added disturbance signals to the robot actuators system while moving to test the respond of the box balancing behavior.

In the simulation program, we model the movement of the box under the assumption that the box moves together with the robot that has more friction. In Figure 10, point A and B are the centers of the robots and point C is the center of the box. We can derive the relationship between the box and the robots as follows.

The equations show the velocity of the box. V_A and V_B represent the velocities of each robot, where V_C and ω_c are the velocity and angular velocity of the box respectively.

$$V_C(t) = \frac{1}{2}(V_A(t) + V_B(t)) \tag{1}$$

$$\omega_c(t) = \frac{V_A(t) - V_B(t)}{L} \tag{2}$$

$$\dot{x}(t) = V_C(t)\cos\theta_3(t) \tag{3}$$

$$\dot{y}(t) = V_C(t)\sin\theta_3(t) \tag{4}$$

$$\dot{\theta}(t) = \omega_C(t) \tag{5}$$

$$\begin{pmatrix} \dot{x}(t) \\ \dot{y}(t) \\ \dot{\theta}(t) \end{pmatrix} = \begin{pmatrix} \cos\theta_3(t) & 0 \\ \sin\theta_3(t) & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} V_C(t) \\ \omega_C(t) \end{pmatrix} \tag{6}$$

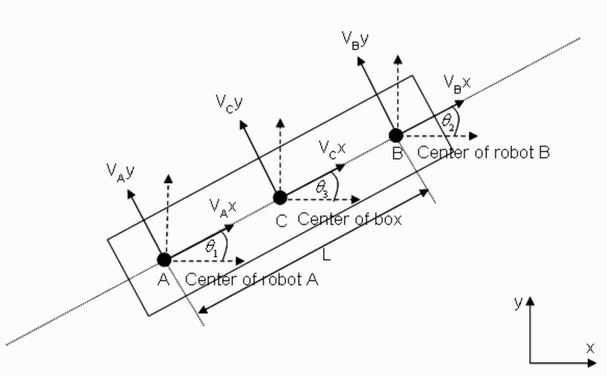

Figure10. Model of Box's Movement

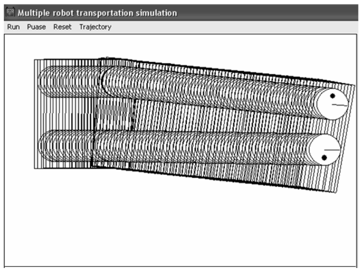

Figure11. Robot movement after adding a disturbance signal to the system

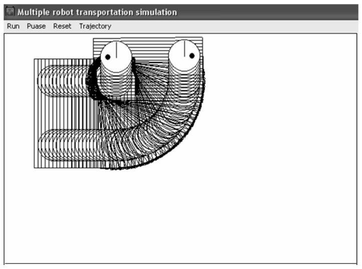

Figure12. Robots turning left by one robot acting as a rotation point and the other rotating in circular motion around that point

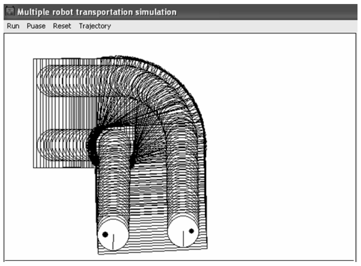

Figure13. Robots turning right by one robot acting as a rotation point and the other rotating in circular motion around that point

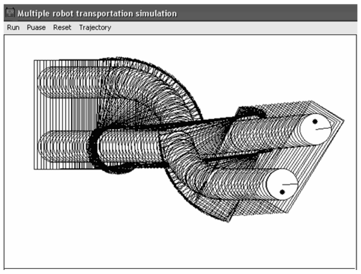

Figure14. Robot passing through a narrow passage

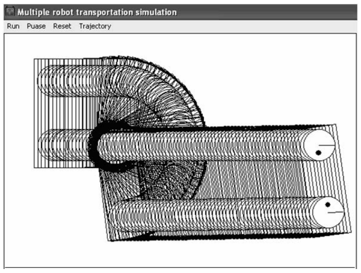

Figure15. Robot switching their position between left and right

V. EXPERIMENT WITH MULTIPLE MOBILE ROBOTS

The proposed control algorithm was implemented in the experimental system, which consisted of two mobile robots with one degree of freedom, as shown in Figure 3. The environment is a flat square area (400 cm x 280 cm), as shown in Figure 16. The opaque plastic box to be transported has a dimension of 21 cm x 61 cm x 7 cm.

We did four sets of the experiments. In the first set of the experiments was used to evaluate the achievement of the forward movement for two mobile robots coordinately. The box are carried from the start point to the finish point for about 4 meters, and the box does not fall down from the robots' tops. This experiment was success 12 times out of 15 times.

The second set of the experiments was the synchronous turn of two mobile robots. In this task, we tested the robot turning left and right. The robots have to carry the box from the start point and turn concurrently while maintaining the box on their top. From 15 runs of each test, the robots turned left successfully 10 times and turned right successfully 9 times without making the box fall down.

The third set of the experiments was the synchronous movement to pass a narrow passage. In this task, the robots carried the box from the start point and switch from the vertical line to horizontal line in the middle of the path before passing the narrow passage. After that, the robots resumed their vertical forward direction and proceeded to the goal. This experiment was success 8 times out of 15 times. The number of success is low because sometimes the robots hit the obstacles while moving pass through them.

The fourth set of the experiments tested the role interchange operation between the robots. The robots carry the box from the start point and swap their position between left and right. After that, the robots moved to the goal. This experiment was success 10 times out of 15 runs.

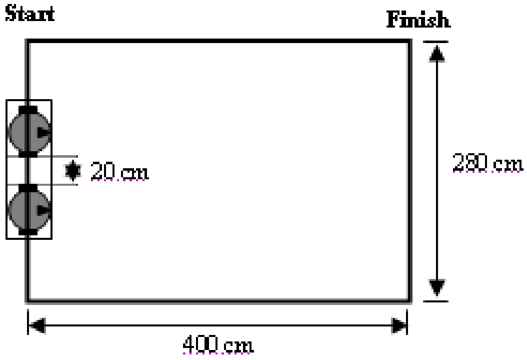

Figure16. The environment used in our experiment: The initial and the goal positions of the robots are shown.

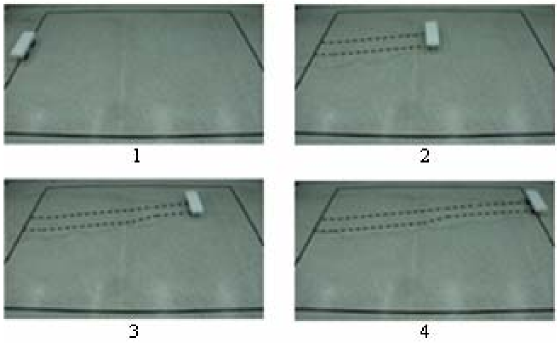

Figure17. Two robots move from the start point to the finish point.

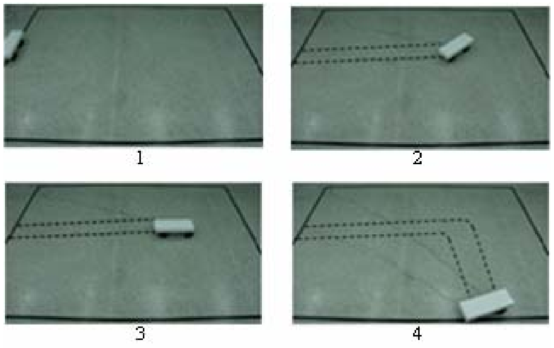

Figure18. Shown are two robots turn synchronized.

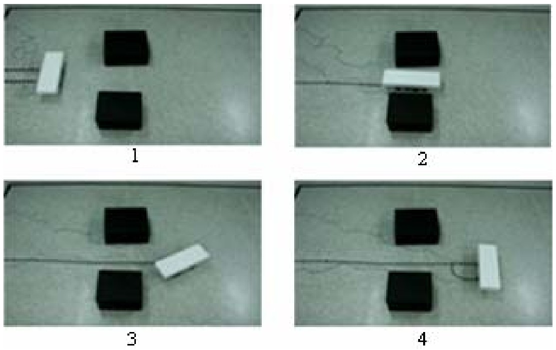

Figure19. Two robots pass a narrows passage.

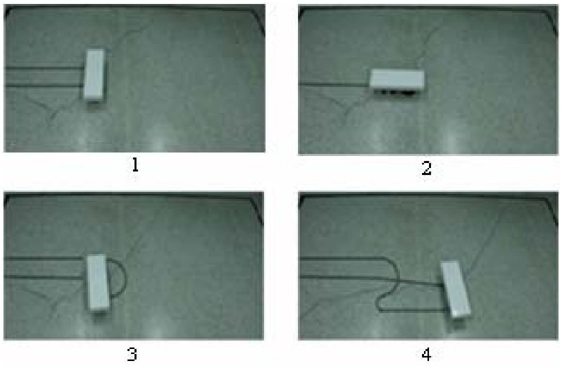

Figure20. Two robots interchange row.

TABLE I. EXPERIMENT RESULTS

Synchronous behavior	Experimental results		
	Numbers of experiment	**Success**	**Not success**
Move forward synchronization	15	12	3
Turn left synchronization	15	10	5
Turn right synchronization	15	9	6
Passing the narrow passage synchronization	15	8	7
Role interchange synchronization	15	10	5

The table summarizes the results on four experiments. Each experiment was run 15 times with different initial positions. In the first experimental result, the robots achieved the goal about 80%. In the second experimental result, the robots have a success rate of 66.67% in turning left synchronization and 60% in turning right synchronization. In the third experimental result, the robots accomplished the goal about 53.34%. This is the lowest rate because there are obstacles presented in the environment. In the final experimental results, the robots achieved the goal about 66.67 %.

VI. CONCLUSION

In this paper, we presented our approach towards the cooperative overhead transportation of a box by decentralized mobile robots. We demonstrated the use of a behavior-based robot system to handle a tightly-coupled task with decentralized control. The results from both simulated and real-world experiments showed that the cooperative box carrying task can be achieved using decentralized control with regular behavior-based architecture. The success rate of moving from a start point to a goal point at around 4 meters away ranges from 50% to 80% depending on the complexity of robots' movements.

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