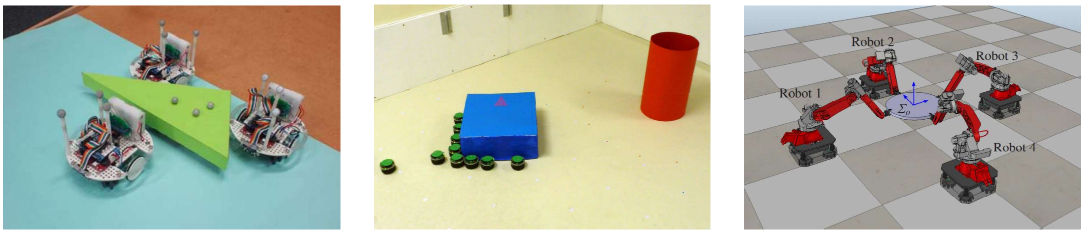
1. INTRODUCTION

This paper introduces new method of object transportation using multi-robot system. A multi-robot system is defined by a system that consist more than one robot. Multi-robot system can be applied at various tasks. One of the scenarios where multi-robot system can be employed is object transportation. Various ways of object transportation are discovered and studied in the past. A multi-robot system of object transportation can be effective and helpful in a variety of applications that can bring high economical impacts; e.g., hazardous material retrieval and disposal, warehouse robots used to carry an heavy objects [1]. The cooperative multi-robot system applied in the object transportation can make the transportation more time efficient and reduces the risk from handling heavy or hazardous objects.

1.1 Background

Object transportation using multi-robot systems has been a popular research topic due to its robustness and fault tolerant features. Over the years, significant improvements in individual robot capabilities for object manipulation and coordinating with others in a group have been observed for successful implementation of multi-robot object transportation in the field. As a result, traditional and popular methods of object transportation by multi-robot systems have remained confined to grasping [2], pushing [3] and caging [4] strategies.

Pushing strategy uses the multi-robot system to generate push force on the object and causes the displacement. To successfully transport the object, robots should be able to generate enough force to overcome the external force applied on the object such as friction between the object and the ground. Grasping strategy includes multiple robots that has function that can physically grasp the object in order to transport the object. Once the object is grasped, the robots starts to transport the object in desired path. Caging strategy encloses the object in certain formation of the robot to make sure that the object follows the planned path. It is similar to pushing strategy but the caging strategy maintain the enclosure during the transportation.



(a) Caging Strategy [5] (b) Pushing Strategy [6] (c) grasping Pushing [5]

Fig. 1.1.: Traditional strategies of object transportation

1.2 Problem statement

The traditional methods are already applied in various application and still lots of related studies are on-going. These strategies are effective and widely used. However, these strategies still have some limitations and possible improvable points as follows:

- Pushing strategies can be limited based on the weight of the object. Each robot should be able to produce enough force to overcome the external force applied on the object. This can be crucial once the multi-robot system tries to transport a heavy object.

- Alignment of the robot has to be precise to translate the object in desired path. Both caging and pushing requires precise formation control and alignment control. To follow an arbitrary path with curves and sharp turns, the alignment and formation needs to be precisely controlled.

- Grasping strategies limits the material of the object to be transported and each robot should have grasping function that can physically hold the object and the robot.

1.3 Research Question

In this paper, we are trying to address the listed limitations by introducing new method of object transportation. The new strategy is called object carrying method. object carrying method is a multi-robot system consisting multiple spherical robots [7] [8] with the functionalities of rolling in omni-direction. The multi-robot system will carry the object and transport it using the rotational movement. The spherical design of the robot brings agile and efficient translation. The strategy does not requires complex inter-agent coordination as long as the object is supported. With the assumption of no slip condition between the object and the robot, the as the robot travels in a speed of v, the rotation of the robot causes the object to travel in speed of $2v$. Due to the difference of the traveling speed, the robot falls behind while the object is traveling. This can cause the instability of the object. Thus, the allocation of the robot is the critical in this strategy.

An effective allocation of multi-robots can assure rapid transportation while maintaining the stability of the object. The stability is maintained as long as the center of the mass of the object is geometrically within the polygon that is formed by outer groups of robots. It also ensures even distribution of the weight of the object on each carrying spherical robots to minimize the individual effort during the transportation process. Unlike the other object transporting strategies, Object carrying strategy performs better with heavier objects. This is because the weight of the object is directly related to the friction between the object and the spherical robots. This friction allows less slip during the rotation of the robots. This mechanism allows the object to be transported to the desired point without requiring any special features for pushing or grasping.

For the successful transportation using object carrying strategy, a fundamental problem is the allocation of robots. Computing the proper formation of the multi-robot system can ensure the stability of the object and avoid over-dependency of weight for robots while transporting. Thus, we present a Grid-based Cyclic Robot Allocation (GCRA) method in this paper. The robot allocation for object carrying strategy should consider the object's properties such as shape and the location of center of mass. By using these consistent data, robots will be allocated. The allocation includes the horizontal and vertical gaps of the grid. The computed design of the grid and the desired path of the object can compute the minimum robots required to transport. Computed parameters of the grid will ensure the stability and the completion of the efficient transportation of the object. Therefore, the research question is *what is the most efficient allocation strategy to ensure the stability of the object during the transportation while using minimum number of robot required?*

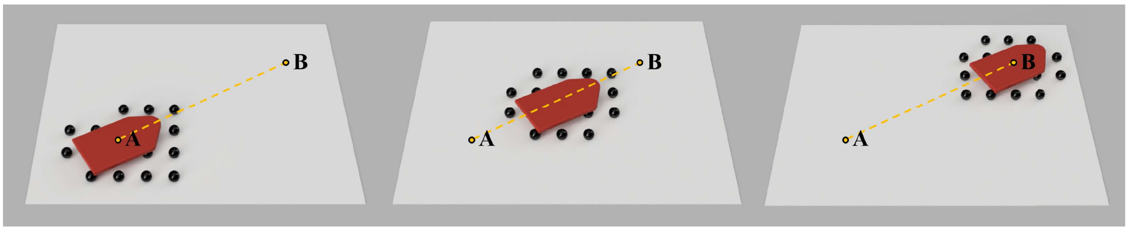


Fig. 1.2.: Object carrying strategy using multi-robot system. The point A indicates the starting position of the object and the point B indicates the goal point of the object.

1.4 Assumptions

To focus on the theory and the mechanism of the GCRA, some assumptions are applied. The assumptions will help to understand the theory and help to focus on the core of the strategy. The assumptions are following:

- The system is centralized and position of each robot and the object is known. Each robot has accessibility of the object and other robot's position.
- The object has a point contact and there is no slip between the object and the robots. This is to ensure that the rotation of the robots can directly impact the transition of the object. In addition, the point contact assumption ensures that action to change the heading direction of the robot does not cause any movement of the object.
- The object has a flat surface on the contact with robots. This ensures that the all the supporting robots has point contact on the object.

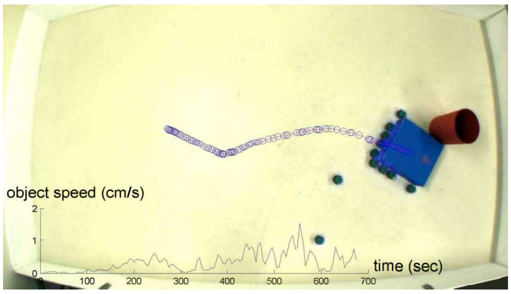
2. RELATED WORKS

2.1 Pushing strategy

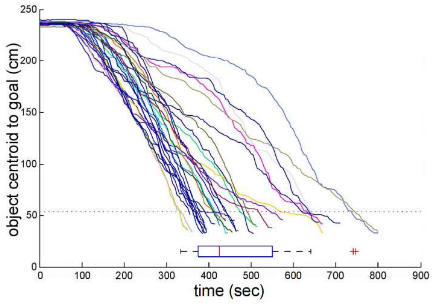
Pushing strategy is the methods of using multi-robots that are not attached to the object. Multi-robots exerts pushing forces on the object to overcome frictional force, gravitational force and other dynamical force during the transportation. The pushing strategy may appear to be simple but this strategy has challenge of alignment of the total force created by each robots. The object can be move on a inefficient trajectory unless the robots gently manage the external forces to stabilise the direction of transport. Most of the pushing strategies are based on homogeneous groups, where the controller of the robot is designed using a behaviour-based methodology [9].

One of the application using the pushing strategy is done by Gerkey and Matarić [10]. The application contains three robots in which one robot of the group acts as a watcher, and the other two robots act as a pusher. The watcher detects the object and the final goal point. The main task of the watcher is to lead the multi-robot system by communicating and providing the information regarding the direction towards the goal. Main function of pushers is to provide enough push force to push the object without sensing or observing any information related to goal position. The main advantage of the strategy is that it can avoid any obstacle on the desired path. On the other hands, alignment of the robot has to be precise to translate the object in desired path and pushers should be able to produce enough force to overcome external forces on the objects.

Another application is done by Chen and Gauci [6]. This uses swarm of mobile robots to push the object to the desired goal. By using the finite state machine, each robot relocates to push the object. Each robot has 8 proximity sensors to detect the object and one color sensor to detect the object and the goal. The core technology of this mechanism is to use well designed finite state machine to achieve the goal in decentralized system.



(a) Object centroid to the goal - Pushing strategy [6]



(b) Displacement tracking - Pushing strategy [6]

Fig. 2.1.: Result of pushing strategy using swarm robotics.

As it can be seen from the 2.1, The multi-robot system successfully transported the object for all 30 trials. However, the variation of the time to reach the final destination is huge which implicates that the mechanism is not the most efficient to find the path to reach the goal. This maybe caused by inefficient alignment of the robots to generate the push force.

2.2 Grasping strategy

Grasping strategy transports object by a robot that is physically attached to an object. Therefore, grasping strategies can be accomplished using robots with the grasping mechanism such as robotic arms. One of the widely used mechanism along with grasping is lifting mechanism to perform a motion of lift and transport. Compared to other strategies, grasping strategy provides a better control of the object once it is grasped and lifted. However, re-positioning of the object using this mechanism is dependant on the weight of the object, graspable area of the object and the materials of the object which can change the coefficient of frictional.

Similar to the watcher and pusher strategy, a leader and follower approach is also applied by Wang and Schwager [11]. The application introduces a multi-robot system to transport an object using a group of four robots. The leading robot pulls the object and perceives the direction towards the goal and other three robots pushes the object to produce enough force. The control model requires information beforehand such as mass of the object, friction coefficients and total number of the robots forming the group. This is to compute the velocity and acceleration at the centre of mass of the object. Each robot has a gripper of single degree of freedom to grasp the object.

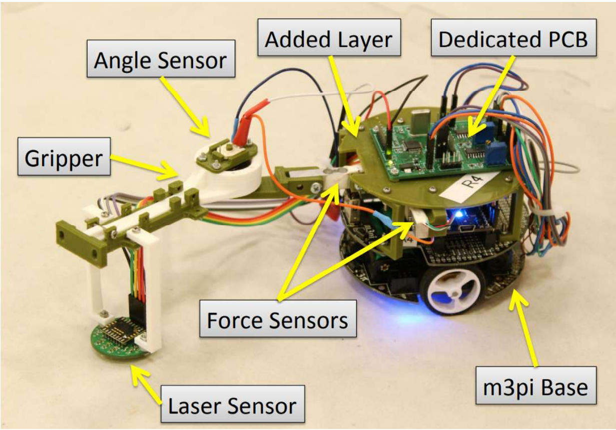


Fig. 2.2.: Custom-built manipulation robot used to grasp the robot which includes various sensors for the force feedback system.

As it can be seen from the 2.2, The robot requires various functions to grsp the object. The design for each robot is complicated and requires lots of data handling for each robot. The robot is customized to perform task with light weight object but if the study is extended to transport a heavy object, robot is required with higher functionalities which is not economical.

2.3 Caging strategy

Object transportation by caging strategy has similarities with pushing strategy. Caging strategy intentionally encloses the object by group of robots and ensures that the object follows the planned trajectories. From the start of the transportation to the end, the object will be surrounded to avoid any desertion from the enclosure. To build a efficient caging strategy, the object's size and shape are important features to create multi-robot system that can complete the task using minimum number of robots required. The main challenge of the strategy is the allocation and positioning of robots.

One of the application using the caging strategy can be described in [12]. It uses three robots that can travel in omni-direction and applied force controller to the robotic system to transport an object. This study clearly shows the difference from watcher and pusher strategy [10]. The difference is that the leader robot only produces force to transport and object while the other robots holds the object by creating a cage. Robots detects the resultant force of the object and acts as a feedback of the controller. This allows following robots to maintain the shape of the cage or the formation. The limitation of the mechanism is that accuracy of following the arbitrary path is low especially with sharp turns.

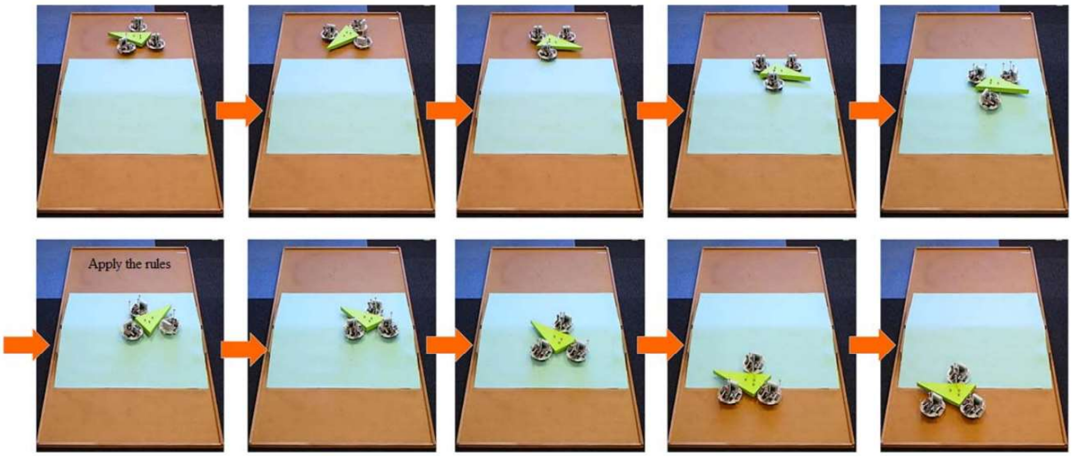


Fig. 2.3.: Custom-built manipulation robot used to grasp the robot which includes various sensors for the force feedback system.

As it can be seen from the 2.3, The object was successfully transported to the goal position in the condition of unbalanced ground. However, the success rate varies based on the posture of the object. The success rate for certain orientation of the object is very low. This indicates that the orientation and the allocation of the robot while transporting needs to be perfect and maintained. Unsuccessful control for each robot to maintain the enclosure will cause the failure.

Application for multi-robot systems has been extensively studied. Multi-Robot Systems (MRS) is defined as a system that includes more than one robots to achieve a task more efficiently. The application for MRS includes indoor mapping, wide range communication and object transportation. For object or payload transportation, MRS is widely used to achieve a task more efficiently using more than one robot. MRS is essential because it can accomplish the goal more quickly with less effort on each robot. Object transportation using MRS has been extensively studied in literature with focus on some traditional strategies. The strategies are pushing, grasping and caging strategies. Various mechanisms and approaches for traditional methods are studied and it is recently reviews by Tuci *et al.* [13]. It categorized the object carrying methods under grasping strategies since the robots align their forces and sustain the transport without losing physical contact with the object.

Some of the earliest work on multi-robot object carrying were proposed by Stilwell *et al.* [14] and Johnson *et al.* [15] where a group of ant-like robots transported palletized loads of unknown mass and center of geometry in a distributed system. Coordination between the robots was achieved based on sensing the forces applied on the object by the robots. Similar coordination in object carrying were later implemented in [16] and [17] with a leader-follower approach.

In the early work of Grid-based Cyclic Robot Allocation [18], The result stated that the grid-based robot allocation could transport the object. The design of the grid is solely based on the object's shape and center of mass of the object. The strategy was successfully tested with the Mat-lab simulation. As it can be seen from the 2.4, the simulation of the transportation was successful in terms of stability of the object and the achievement of the given task. However, the study considered the movement of the transportation in only one direction with single path. This does not fully ensures the success of the transportation and needs to be tested in higher dimension.

In this context, we emphasize the significance of GCRA proposed in this paper in Section 4, that it does not require further computation or adjustments in robot allocation for object carrying in two dimension once the initial cyclic grid system is initialized. The proposed grid generation method is solely based on the properties of the object. The method is

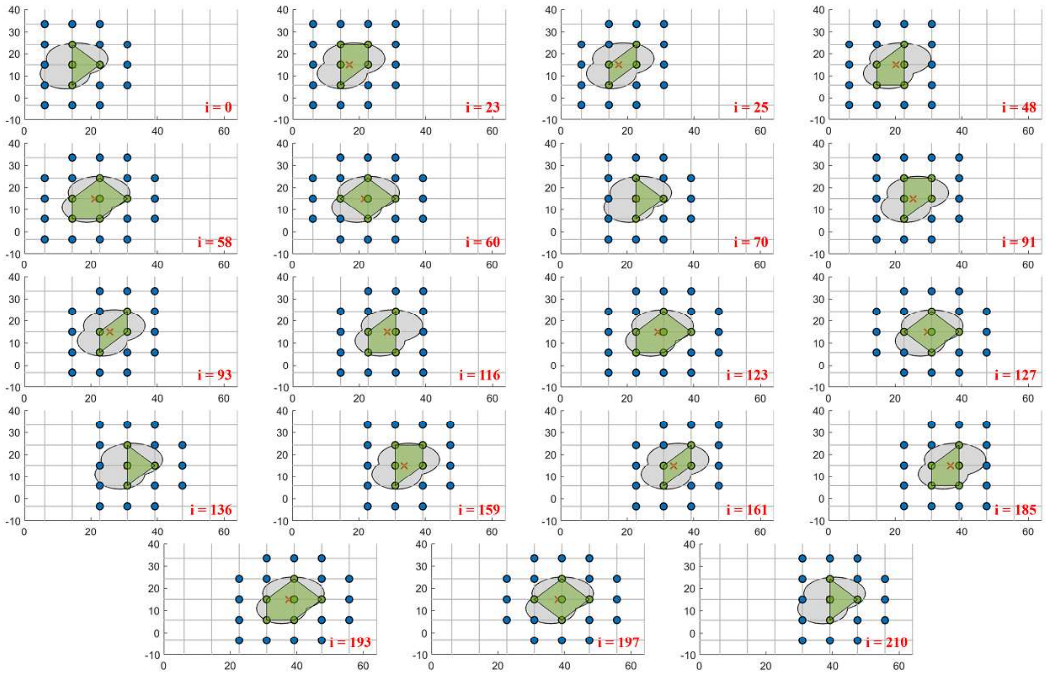


Fig. 2.4.: Result for Early GCRA method using an arbitrary shape 1. The direction of the transportation is in x-axis only.

applicable for multi-robot system consisting group of spherical robots that does not require extra functionalities except rotation. The proposed grid generation method allows planar omni-directional translation as shown under grid analysis with proof of stability in Section 4.0.3.