Study of Object Conveyance Using Multiple Mobile Robots with Dynamic Team

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CHAPTER 1

Introduction

In the recent years, multiple mobile robot systems (MMRS) types of research have grown significantly. The concern is given by the robotic researchers to this study is motivated by the variety of the potential application which can be carried out by a group of the robot, such as exploration, agricultural foraging, military, warehouse, search, and rescue, and cleaning [1] [2] [3] [4].

The object conveyance as known as "piano mover problem" is a well-studied topic in multiple mobile robot systems where robots are expected to transport a box to a destination cooperatively. In this task, the robots are expected to reach the main goal of transporting an object to a goal location as well as the maintenance several condition including approaching the object with a formation, maintaining closure with the object and maintaining straight movement [5] [6]. The use of multiple mobile robot systems in object conveyance is chosen because it offers several advantages that single robot cannot achieve such as fault tolerant, efficiency, low cost, and flexibility [1]. However, the formation and motion control may become more difficult because of the increase in sensor information and actuators since the number of the robots is increased [7].

The robots coordination is one of fundamental issue that needs to be addressed in multiple mobile robots system. The term of coordination is referring to the assignment of robots action so that the efficiency of the team is maximized [8]. This coordination involves many subjects like optimizing communication networks, maximizing sensors output data and coordinating power usage through distributed power source [2]. It is used for either homogeneous or heterogeneous team of robots in several tasks such as exploration, mapping, object conveyance, target tracking, art performance etc. [2] [8] [9].

In the object conveyance, there are several approaches which are proposed by researchers. They are categorized by the number of the robot and supporting tools. The number of robot used in the system affects how the robot coordination and motion are addressed. A low or a minimum number of robots (two robots) can move an object using force closure. This approach enables the robot to grasp the object tightly with strong external force, preventing the object from rotation or shifting anywhere [10] [11]. Other techniques which employ three to nine robots may use form closure [12] [13] and caging technique [14]. Form closure is similar to force closure but it does not require external force. It works by encircling an object from every direction and the transport object to its goal position. The caging technique is analogous to form closure but involves less wrapping. The robots in these techniques have extra space between its position to the object and another robot. Another technique is used by multiple mobile robot systems with ten to hundreds robots which located closely between one robot to another robot. The occlusion based technique is reported in [15] and granular convection approach is proposed in [16]. The cooperative control based on real and complex valued neural networks are proposed respectively in [17] [18].

The approaches based on supporting tools used by the robots have been reported. The supporting tools vary to gripper [19] [20], string [21], stick [22], and attachment [23]. The coordination techniques based on the number of robots are often used for a predefined object with regular shapes such as rectangle [24] and triangle [25]. In addition, supporting tools based approaches can be employed to move specified object which are limited and difficult to be substituted by other object [23] [19]. The use of string offers the flexibility of object transportation [21]. It can be used for moving a lot of the object shapes. However, controlling object position becomes difficult and special mechanism of the robot is needed. Therefore, the implementation of this technique is not suitable for small mobile robot which has simple control and mechanical structure.

The object conveyance problem exists in many places such as a house, office, warehouse, and agricultural house which have many kinds of the object with different shape and weight. The object might be moved by using only one or two robots with simple push action. And it may need more robots to move because it is heavy. Because of the number of robots used in the team depends on the target object, the coordination technique for object conveyance problem using mobile robots that can adapt to any kind of object without prior information of its shape is needed. The adaptable number of mobile robot in a team can be addressed by dynamic team strategy. The dynamic team strategy is a method for assigning robot number in a multiple mobile robot system where the mobile robots are a temporal and changeable team whose association properties are allowed to alter over time [26] [27]. That is, teams dynamically and automatically grow and shrink, and the member may be substituted. Therefore, it enables multiple mobile robot systems becomes more efficient in the use of the robot [28] [29].

In order to realize this strategy, the object conveyance using multiple mobile robot systems is defined into following specification. First, the communication system is explicit where each robot can share any related information through broadcast message. It is required to know of actual process to take further action. Second, the position information of the robot, target object, and desired trajectory are known by each robot. Therefore, the positioning system is required to obtain their positions. Third, the decision making is decentralized that the robot move independently without any interference from other robot. Fourth, the mobile robot used in this research is a non-holonomic two wheeled robot with circular shape. Its diameter is 7cm with at least five distance sensors installed for navigation.

The beginning of the dynamic team is using one robot for recognizing target object shape and size. It is named as surveyor robot. It approaches the target object by referring target object position which is obtained from positioning system. Then, the surveyor robot surrounds the target object to measure distance from robot to the object by using installed distance sensors. The recorded distance data are processed using Graham Scan algorithm to make a convex hull which is used to estimate object shape. After that, object corner positions are obtained and between them, push points are determined. The push points estimation method for regular and irregular object is proposed in [30]. This push points is used for surveyor robot to make initial push. In this step, surveyor robot will experience that the object is light or heavy. Collision signal can be used for determining an object weight with a push [31].
The rest of dissertation is organized into five chapters.

In chapter 2, the most relevant research work in the areas of coordination in object conveyance using multiple mobile robots and related subject is described.

The objective of this chapter is to survey and compare the proposed strategies by analyzing its advantages and weakness.

In chapter 3, the information of the concept and implementation of the dynamic team for coordinating a team of multiple robots using the two-dimensional motion of physics module, a python library for robotic simulation are provided.

In chapter 4, the simulation and experimental results are revealed and the properties of the dynamic team approach are discussed.

In chapter 5, a final chapter summarizes the work, provides final conclusions and potential application of this research. The referenced works in this document are presented in a separate references section. Also, several relevant appendixes are provided.

CHAPTER 2

Object Conveyance using MMRS

2.1 Introduction of object conveyance

In the mobile robot research area, object conveyance problem is related to the well-known as the “Piano Mover’s Problem”. It is that of finding a continuous motion which will take a given object from a given initial position to a desired final position, but which is subject to certain geometric constraints during the motion as illustrated in Fig. 2.1. These constraints forbid the objects to come in contact with certain obstacles to collide with each other [32]. It is also known as the box-pushing [33], object manipulation [21] [22] and the object transportation [34] [35].

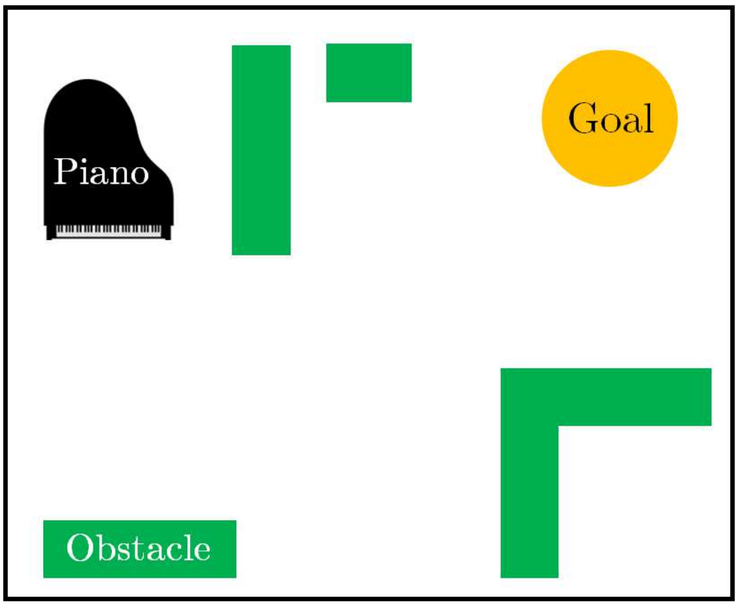


Figure 2.1: Multiple mobile robots object conveyance

The object conveyance consists to cooperatively move an object comparatively large when opposed to the size of the robots, from a start location to another goal location using robots that are only capable of pushing movements. This subject has many potential applications that can be emphasized with following examples: search and rescue, carrying out hazardous works, automatization of industrial processes, and movement of heavy objects [36].

At present, there are several approaches with regard to the object conveyance using multiple mobile robot systems. There are some popular approaches like the "Object closure" where the object position can be controlled by a team of robots that surround the object, so the object position will be controlled by the movement of each robot that surrounds and pushes the object [12]. It is preceded by "object grasp" where robot to grasp the object tightly with strong external force, preventing the object from rotation or shifting anywhere. Another well-known approach is the "Multiple Mobile Robot System -Watcher" where a robot (watcher) beholds the movement of the object, while coordinating the operations of the robot team (pushers) that physically manipulate the object [36].

Some recent works use the "swarm intelligence" model where self-organized systems of homogeneous robots are built around simple behaviors, obtaining a decentralized and intelligent global behavior [37]. Also, some approaches are based on artificial intelligence tools, as the reinforcement learning or "Q-Learning" [38]. For more intricate task of manipulation, some authors propose the utilization of specialized robots in manipulation tasks [39].

Furthermore, object conveyance approaches are also carried out in other movement mechanism such as pulling [21] [22], gripping [40] [41], and lifting [42]. These movements need a particular mechanism installed on the robot such as arm, gripper, and other manipulator device. In this research, push movement is used for transporting target object. By using this simple movement, the robot structure does not become complicated than other movement.

2.2 Coordination in object conveyance

Coordination is the important issue in multiple mobile robots research area. There are static and dynamic coordination [43]. Coordination is also classified into strongly coordinated, weakly coordinated, and not coordinated [44]. Static coordination is a coordination method with pre-constructed rules for executing a task which also known as off line coordination [43]. The rules in traffic control problem such as ”keep left”, ”stop in traffic light” And ”keep distance to other robot” are the example of static coordination [45]. Dynamic coordination also known as online coordination is carried out in real time based on the actual information via communication [43]. The static method can handle intricate tasks. However, it is difficult for controlling in real time. The dynamic coordination can well meet the capability of real-time. However, it has difficulty in dealing with more intricate tasks.

In multiple mobile robots coordination, communication is required to enable each robot to collaborate and know the information of the sensor data, position, and the state of an environment with others. Communication is divided into explicit and implicit. Explicit communication enables the robots to exchange their information by using unicast or broadcast messages. This often requires a particular wireless communication module. Currently, coordination methods are mainly utilizing explicit communication. Coordination and its related subjects in multiple mobile robot systems (cooperation, knowledge, and organization) are summarized in [44] and illustrated in Fig. 2.2.

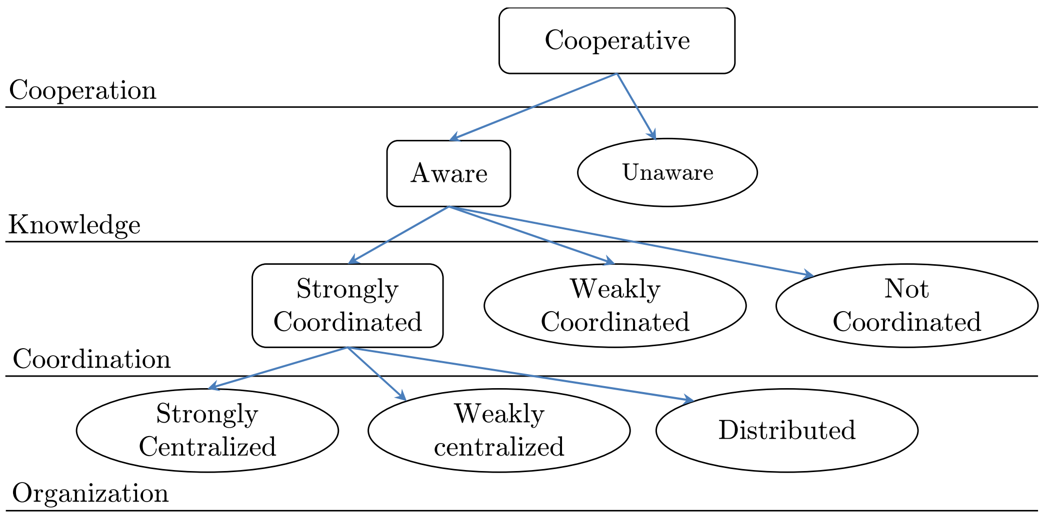


Figure 2.2: Taxonomy of multiple mobile robot systems

Cooperation level is the first level which is concerned to the system ability to accomplish specific task cooperatively. The second level is knowledge level which means the portion of sharing information between robots. A robot with completely shared information from other robot is classified into aware one. On the other hand, an unaware is a robot without any information from other robot. It does not mean they do not communicate each other. In third level, coordination is considered as a cooperation in which the actions performed by each robot in harmony with other robots in such a way that the whole ends up being a systematic and high performance operation. Lastly, in the last level, organization is concerned with the decision-making method in a multiple mobile robot systems. Basically, it is divided into centralized and distributed. And the centralized is classified into strongly centralized and weakly centralized [44]. The proposed method by other researchers in object conveyance coordination related to the multiple mobile robot systems taxonomy is shown in Table 2.1.

Table 2.1 Coordination method in object conveyance problem

Unaware	Adaptive Logic Network [46], Behavior-Based [47], Team Play [48]
Aware not Coordinated	Function Allocation Concept [49]
Weakly coordinated	Not Shared Information [50], Decentralized Test Algorithm [51]
Strongly coordinated Weakly Centralized	Integrated Cooperation Architecture [52], Tightly Coupled Robot Architecture [53], Layered Architecture [54]
Strongly coordinated Strongly Centralized	Constrain and Move Approach [55], Probabilistic Modelling [56], Lifelong Adaption [57], Pusher-watcher [36], Behavior-Based [58]

These methods use a various number of robots both homogenous and heterogeneous. And in this research, a dynamic team concerned coordination method is used for object conveyance problem.

2.3 Cooperative conveyance control

Cooperative conveyance control is used to secure the object conveyance process from start point to destination point while satisfying several required parameter such as maintain object orientation, move on the desired trajectory, and team formation. There are five well known methods for cooperative conveyance control:

2.3.1. Sliding mode control

In control system, Sliding Mode Control (SMC) is a nonlinear control method that changes the dynamic of a nonlinear system. It works by using of a discontinuous control signal that forces the system to slide along system normal behavior as shown in Fig. 2.3. SMC has been extensively used in control systems with uncertainties and external disturbances [59] [60]. It is widely implemented in biomedical [61], power electronic [62], electric vehicle [63], and motor drive [64]. In mobile robot research area, the applications of sliding mode control are reported in [65] [66] [67].

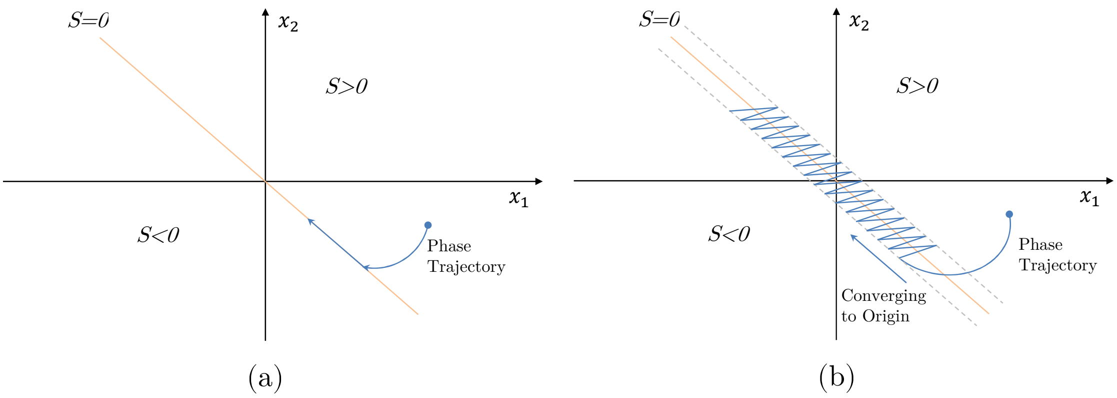


Figure 2.3: Phase plot for ideal SMC (a) and actual SMC (b)

2.3.2. Virtual structure

Virtual structure is an approach of embedding additional unreal robot to the multiple mobile robot structure so they can behave like in real structure and maintain a rigid geometric relationship to each other [68] [69]. It is providing robustness to the formation in the face of perturbations as reported in [70]. The visual structure is based on the idea when a virtual force is given on a virtual structure, then each robot in the virtual structure will move in the direction of the force as illustrated in Fig.2.4. Moving in formation algorithm is carried out in following steps:

(a) Align the virtual structure with the current robot positions

(b) Move the virtual structure by Δx and $\Delta \theta$

(c) Compute each robot trajectories to move robot to desired virtual structure point

(d) Adjust wheel velocities to follow the desired trajectories

(e) Go to step a.

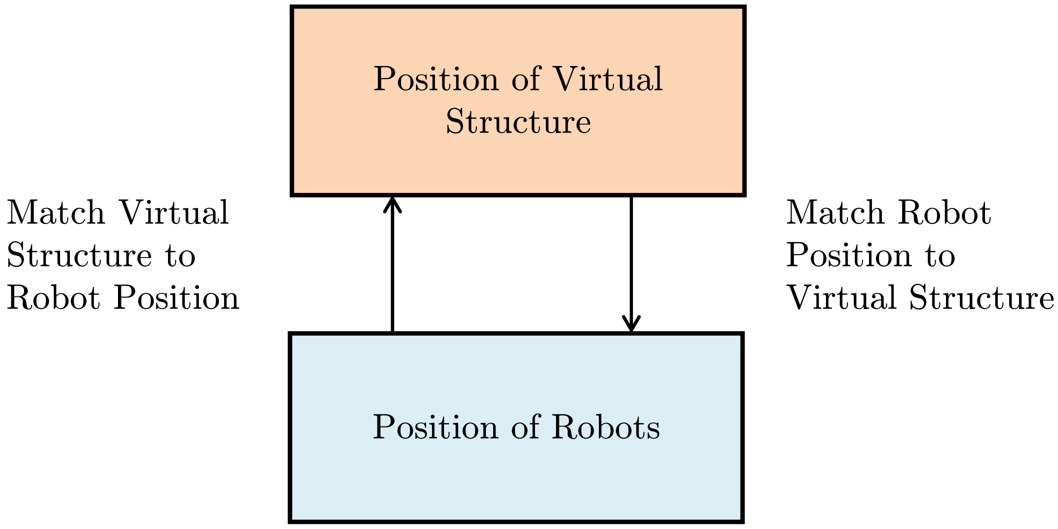


Figure 2.4: Virtual structure flow control

2.3.3. Behavior based approach

Behavior based is a well-known approach which is used by researchers worldwide [71]. It enables a robot to act with several predefined behavior in order to response a stimulus from the environment [72]. A behavior based in object conveyance problem is reported in [73]. The illustration of behavior based of object conveyance in finite state machine is shown in Fig. 2.5. It is also used for mobile robot navigation [74]. Behavior based approach offers a simpler cognition and fast execution comparing to the traditional artificial intelligent. However, the challenge of designing behavior based controller is a problem prioritizing because it needs to be evaluated at design time.

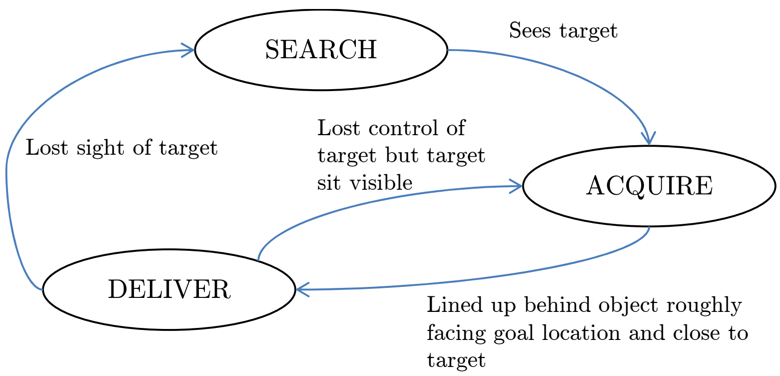


Figure 2.5: Finite state machine used for behavior-based object conveyance

2.3.4. Swarm intelligent

Object conveyance is also carried out by swarm intelligent (SI) since it is one of the biological inspired problems from ant colony in the nature. The famous used SI approaches are ant colony optimization (ACO) and particle swarm optimization (PSO). The ACO is a probabilistic technique for solving computational problems which is used for finding optimal path through graphs based on behavior of ants [75]. Cooperative conveyance by ant and robot are reported in [76] [77] [78]. They replicate ant behavior into a model and implement it to a robot system successfully.

The PSO is an approach in computer science which optimizes a problem by continuously trying to improve a particle solution with regard to the evaluation of objective function at each particle [79]. In object conveyance problem, the implementation of PSO is reported in [80].

2.4 The origin of dynamic team

A dynamic team is an approach where the number of joining robot in a multi-robot team is varying depends on the assigned parameter such as shortage of power and system failures. This approach needs several properties of association in order to describe the ways in which robots are associated with one another. The association properties include sensing capability between each robot, sensing capability of each robot action, communication capability of each robot, cooperative action capability, and practical coordination method [27].

The method of a dynamic team is described into three precise definitions. First, a team of robots is a logical association of members of a set of robots. Second, a dynamic team of robots is a temporary and fluid team whose association properties are allowed to vary over time. Third, the method of a dynamic team is a programming model which addresses the mapping of a task into a dynamic team of robots such that the structure of the team is consistent with the task [27].

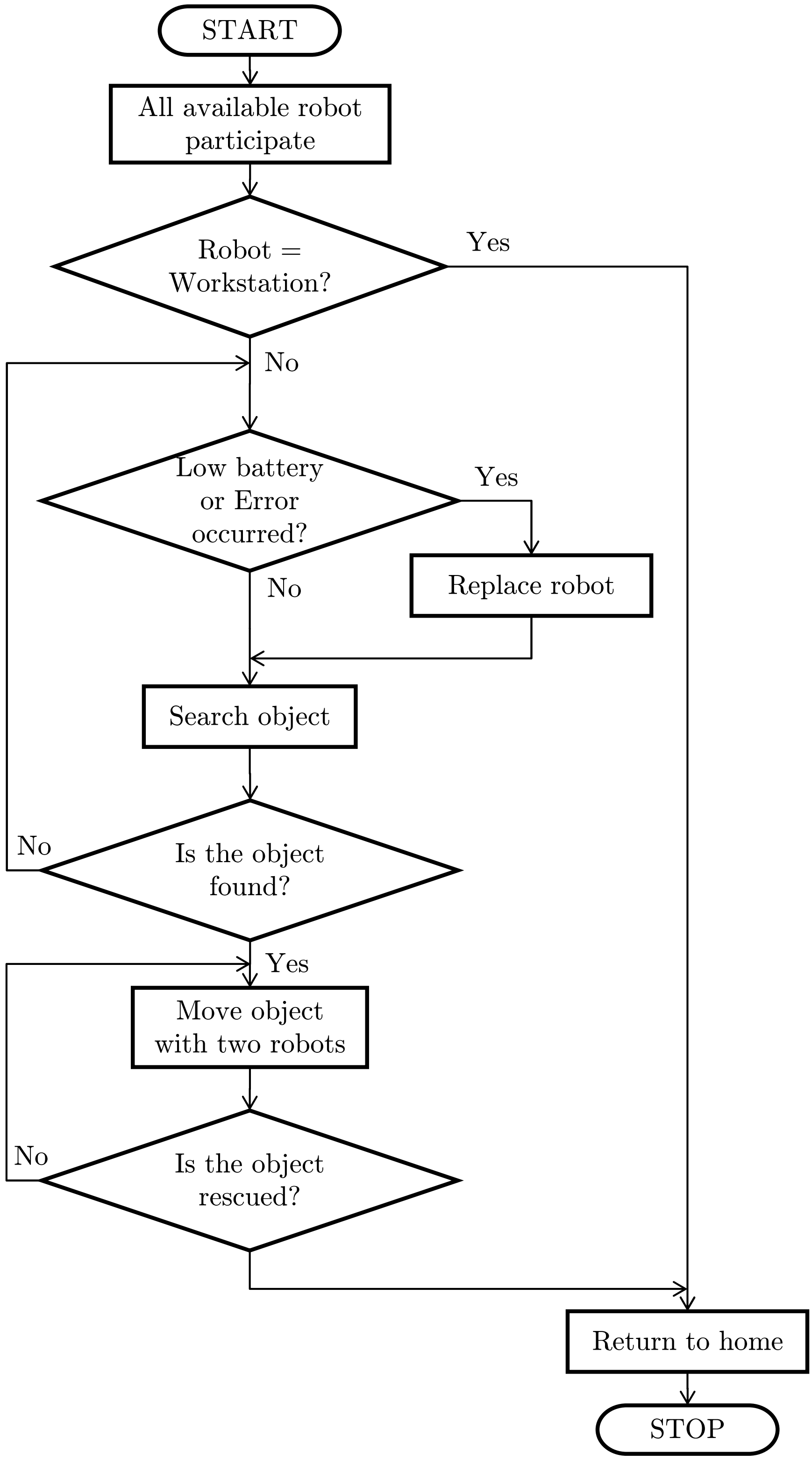


Figure 2.6: The dynamic team flowchart of search and rescue task

An implementation of a dynamic team in search and rescue task is illustrated in Fig. 2.2. The goal of search and rescue task is to search for an object in an environment and retrieve it to safely place. The search phase is carried out in parallelism with many robots searching simultaneously. On the other hand, retrieve phase requires exactly two robots to move a found object to safety place. Finally, the process is finished if retrieval process is complete. In the object conveyance using multiple mobile robot systems, the dynamic team is adopted in this research with particular robot selection method. The number of joining robot is determined by the pose, push position, and weight of the object. Therefore, the related approaches are needed. These details are explained in the following sessions.

2.5 Object pose and push position estimation

In the object conveyance problem, the object pose's (position and orientation) and shape are the important information which is related to the utilization of method in the system. It can be known, partially known and fully unknown. The known means that such all information is taught to the multiple mobile robot systems hence coordination method and control of conveyance become a priority. The partially known means that only one or two information is available. For example, if the object position only is provided for the system, the object orientation and shape are required to be estimated with a particular method. The unknown means that the system blinds to the object and has to obtain such information before carrying out the object conveyance.

Object pose estimation using laser range finder is reported in [81]. The multiple sensing with laser range finder is presented in [82]. They mentioned that the laser range finder can estimate the pose both moving and not moving object. However, the laser range finder cost high and its size is not suitable for small mobile robot. Other method is the utilization of omnidirectional camera with image processing [25] [83]. These methods require high specification controller and it cost relatively high. Another method is the utilization of IR range sensor for implementing simultaneous localization and mapping (SLAM) [84]. It is promising method for small mobile robot since laser range finder is not yet manufactured in small size and it may drain battery quickly.

2.6 Object weight estimation

It has been inspired by the phenomena in nature that ants cooperate to transfer an item much too heavy for each of them to move alone. If an ant experiences a difficulty in the moving object, other ants will come to help. In order to implement this ability to a mobile robot, knowing the condition during pushing the object is necessary. Since the collision signal can be observed by using an accelerometer. The influence of various objects weight on the collision signal which is used for determining the number of robot in a team is presented in [85].

The principal of the approach is based on motion law of Newton. In physics terms, the acceleration a, is the amount by which the velocity changes in a given amount of time. Acceleration occurs when initial velocity lower than final velocity, $v_i < v_f$, but deceleration is the opposite of acceleration where final velocity smaller than the initial velocity. Therefore, value of a is minus for deceleration. The initial and final times over which your speed changes, t_i and t_f, can be written in equation (2.1).

$$a = \frac{\Delta v}{\Delta t} = \frac{v_f - v_i}{t_f - t_i} \tag{2.1}$$

During movement, the mobile robot may generate both acceleration and deceleration. As in line follower robot, the robot will move quickly on a straight line and slow down when turning in order to keep on the specified path. Acceleration occurs at start, and deceleration occurs at curve path. In the object conveyance by using mobile robot, deceleration may occur during collision between the robot body and the object. In Fig. 2.7, the mobile robot with mass m_r moves toward from point p_1 to p_2 to push the box with mass m_b. It is assumed that the rubber wheel has friction coefficient near to 1 and the mobile robot can deliver force with minimum power lost.

In Fig. 2.7(b), the robot collides the box at point p_2. Robot and box are designed with material to make elastic collision that the total momentum before the collision is the same as the total momentum after the collision. Therefore, the velocity of the box $\vec{v}_b$ and velocity of the mobile robot $\vec{v}_r$ after collision can be written in equation (2.2):

$$m_r\vec{v}_r + m_b\vec{v}_b = m_r\overrightarrow{v'}_r + m_b\overrightarrow{v'}_b \tag{2.2}$$

Refer to the equation above, velocity of the mobile robot after collision $\overrightarrow{v'}_r$ may decrease because collision generates momentum of the box. The amount of velocity decrement depends on box mass. Therefore, the mobile robot will decelerate after collision because its velocity before collision higher than after collision. The right side of Fig. 2.7(b) shows the robot velocity change over the time with the peak of the graph is at the point p_2.

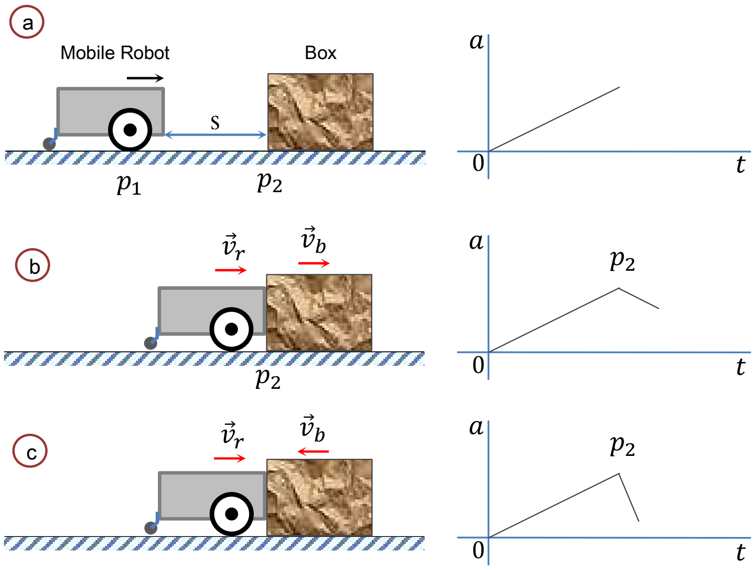


Figure 2.7: Object weight estimation process

Figure 2.7(c) is similar to 2.7(b) but the decrement of the robot velocity at Fig. 2.7(c) is higher than Fig. 2.7(b). This is because the box mass of Fig. 2.7(c) is slightly heavier. Rotary speed sensor and tactile switch can be used to measure deceleration before and after collision. However if these sensors are used, it is difficult to measure velocity due to contact time in millisecond. The alternative is utilizing MEMS accelerometer because it is sensitive to velocity change reference.

Collision signal measured with accelerometer is reported in [63]. It classifies three objects into not movable, easyly movable, and movable. These three collision signals are distinctly illustrated in Figs. 2.8 to 2.10. This method can be used in a robot whoch has wide range of low and high speed to realize a collision. Due to the experimental robots in this research does not have such speed, a similar method represented by object position tracking is used.

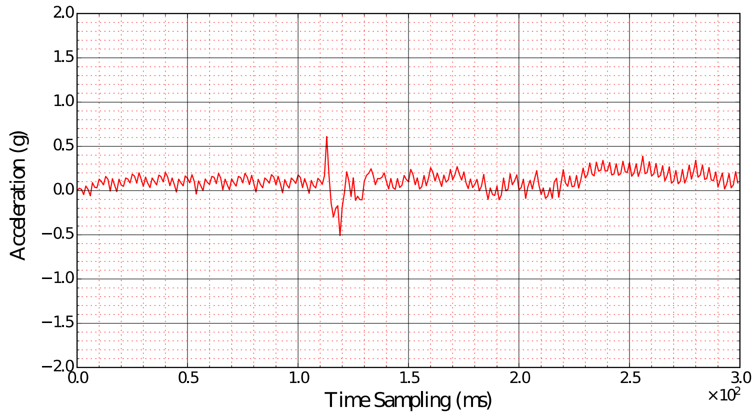


Figure 2.8: Collision signal of not movable object

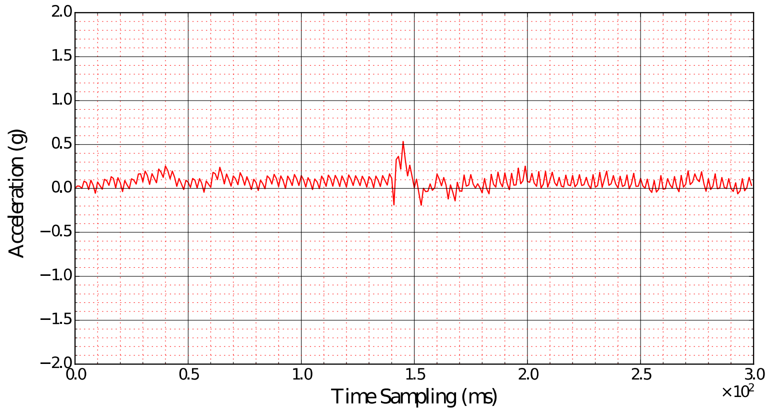


Figure 2.9: Collision signal of easily movable object

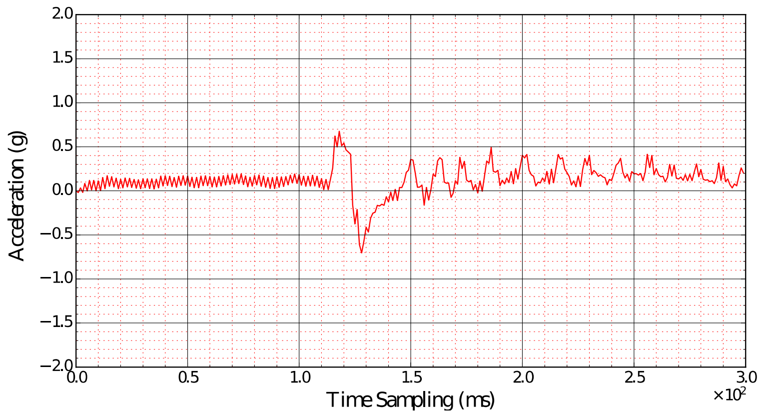


Figure 2.10: Collision signal of movable object

2.7 Mobile robot model

A mobile robot equipped with wheels is a wheeled vehicle which can perform an autonomous motion in their environment which means it is capable of navigating without the need of the physical or remote device. It is categorized into a holonomic and non-holonomic mobile robot. Holonomic is a robot which has same the controllable degree of freedom and total degrees of freedom. If the controllable degree of freedom is less that degrees of freedom, then it is called as a non-holonomic mobile robot. In order to realize the autonomous motion, the robot is driven by a particular control system which related to the robot dimensions, position, velocity and acceleration of each of the link in the robotic system. The mobile robot moves on a two-dimensional plane which is often called as Cartesian coordinate. In this research, a non-holonomic two-wheeled mobile robot and its position in the Cartesian workspace is shown in Fig. 2.5.

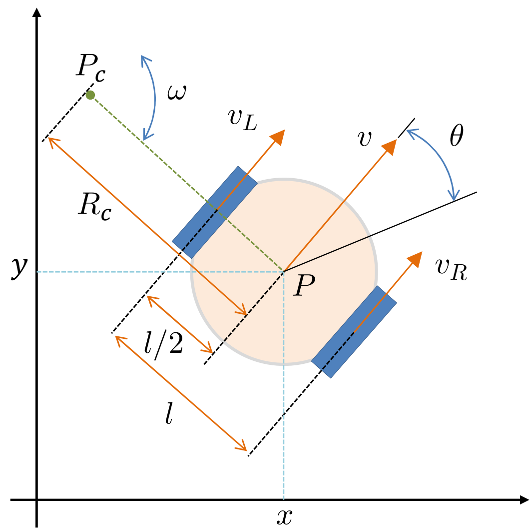


Figure 2.11: Robot position in Cartesian workspace

The two-wheeled mobile robot changes the direction depending on the velocities of each wheel. By changing the velocities of each wheel, the various trajectory of the robot can be taken. Because the angular velocity of the robot ω at reference I_{cc} must be same for both wheels, the following equation can be written in equation (2.3):

$$\omega(R_c + l/2) = v_R \tag{2.3}$$

$$\omega(R_c - l/2) = v_L$$

Instantaneous center of curvature, linear velocity of the right wheel, linear velocity of the left wheel, velocity of robot, and distance between the wheel are designated I_{cc}, v_R, v_L, v and l, respectively. At any instance in time it can solve R_c and ω with equation (2.4):

$$R_c = \frac{l(v_R+v_L)}{2(v_R-v_L)} \tag{2.4}$$

$$\omega = \frac{v_R - v_L}{l}$$

In the Fig. 2.5, the robot position P is assumed at the position (x, y), headed in a direction making an angle θ with the X axis. By modifying the wheel velocities v_R and v_L, the robot can be moved to different positions and orientations. Therefore, the I_{cc} can be found by using equation (2.5):

$$I_{cc} = [x - R_c \sin(\theta)\,, y + R_c \cos(\theta)] \tag{2.5}$$

And at the time $t + \delta t$ the robot pose's is written in equation (2.6):

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} \cos(\omega\delta t) & -sin(\omega\delta t) & 0 \\ sin(\omega\delta t) & \cos(\omega\delta t) & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} x - I_{cc^x} \\ y - I_{cc^y} \\ \theta \end{bmatrix} + \begin{bmatrix} I_{cc^x} \\ I_{cc^y} \\ \omega\delta t \end{bmatrix} \tag{2.6}$$

For special case of $v_R = v_L = v$ (robot moving forward on a straight line) the motion is calculated using equation (2.7):

$$\begin{bmatrix} \dot{x} \\ \dot{y} \\ \dot{\theta} \end{bmatrix} = \begin{bmatrix} x + \cos(\theta)\delta t \\ y + \sin(\theta)\delta t \\ \theta \end{bmatrix} \tag{2.7}$$

CHAPTER 3

Dynamic Team for Object Conveyance

This study is concerned with determining the number of the robot in multiple mobile robots object conveyance. Two-wheeled mobile robots are us

ed with disk-shaped where the wheels are in the same direction to the center of the robot body. The illustration of object conveyance by multiple mobile robots on the world coordinate system $\sum w$ is shown in Fig. 3.1

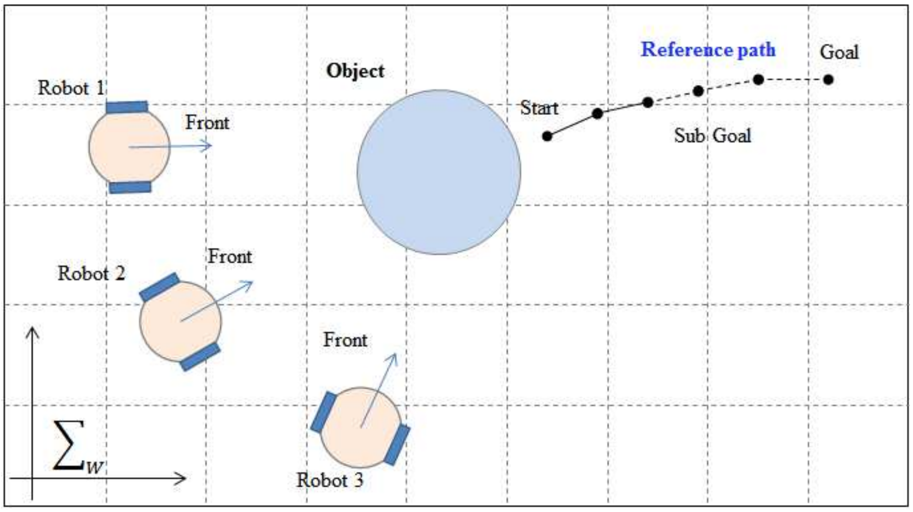


Figure 3.1: Multiple mobile robots object conveyance

3.1 Problem setting

The mission in this multiple mobile robot system is to convey the object on the reference path. To achieve this mission, multiple mobile robot systems are required to estimate object shape and size then determine push point for initial push. Regular and irregular shape object are used for demonstrating the algorithm. Object conveyance with a minimum number of the robot is also required to be demonstrated in order to verify the validity of the algorithm. These missions are carried out on an obstacle free workspace. Therefore, an additional algorithm for avoiding the obstacle is required for actual environment. In order to specify the scope of our proposed algorithm, the assumptions about our task are made as follow.

- All robots have circle shape body which can contact with the object in any direction.
- Non-holonomic two-wheeled robots are used.
- It has eleven distance sensors placed at the front-side of half-body to measure distance and direction on the robot direction toward any other object as shown in Fig. 3.2(b).
- A target object is placed on specified position.
- The actual environment consists of many objects as constraint or obstacle. However, to simplify the process, robot and a target object are located on an obstacle free workspace.
- Each robot positions on the world coordination are known.
- Distance sensor reading is included with 0.2% random noise.
- The robot knows object position but has no information about object shape, size, and weight.
- Reference path consists of several sub-goals. On the reference path, an object is required to be conveyed on the sub-goals within 8 seconds

3.2 Algorithm

In this object conveyance problem, an object is moved by pushing it. To make push mechanism, the position orders are destination, object and robot. If the object is facing toward to the destination, then the robot position in the behind of the object. However, the robot will not able to determine where is the correct position for a push if object shape is unknown.

The flowchart of proposed algorithm for the dynamic team is shown in Fig. 3.3. The determination process of the robot number is first four blocks, and the rest three blocks are the conveyance process in general.

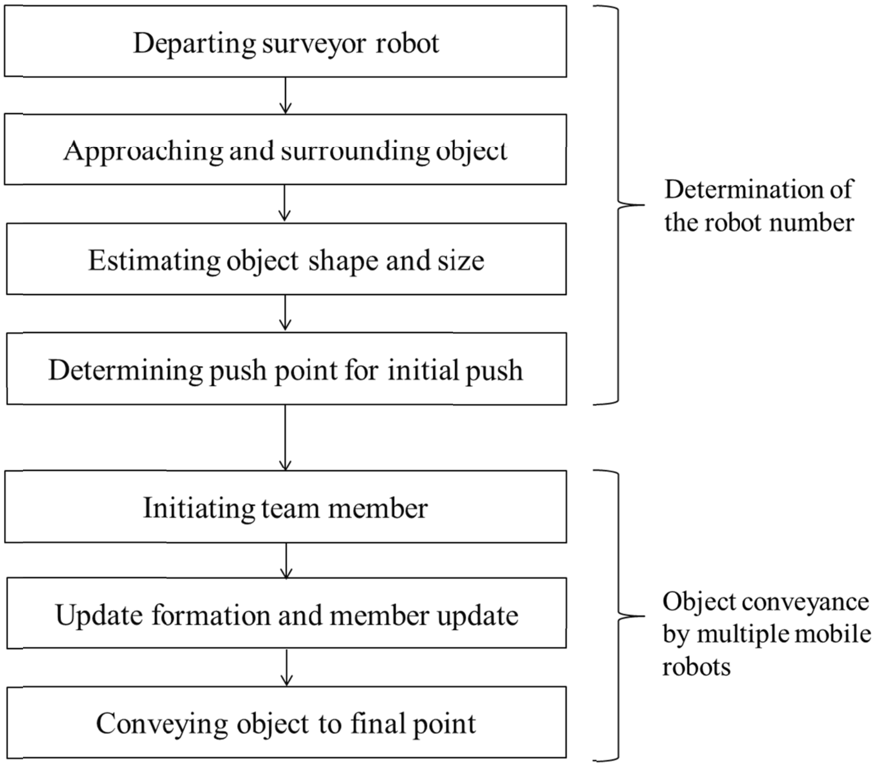


Figure 3.3: Proposed dynamic team flowchart

3.3 Departing surveyor robot

A robot which is used for estimating object shape and size is called surveyor robot. The surveyor robot can be selected among the robots which have closest distance to the object. However, random selection is chosen because the robots are located near each other. Also, the surveyor robot knows object position through positioning system. In practical, the positioning system can be an image, frequency, light or sound-based device which has advantages and disadvantages between each other. And in this simulation, position data can be obtained easily.

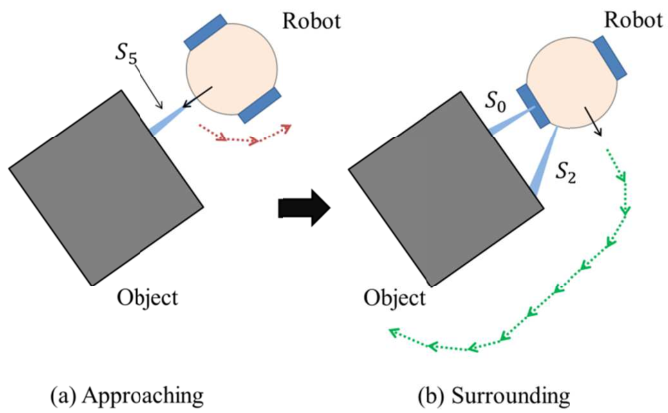


Figure 3.4: Approaching the object for measuring

3.4 Approaching object

Since the surveyor robot is departed from the start position and it will approach directly to the object. During the travel, the robot can avoid the collision from other robots by detecting them using distance sensor. In order to determine robot avoidance movement for i-th robot, right side $D_r^{R_i}$ and left side $D_l^{R_i}$ sensing data are calculated and compared to get angular velocity ω by using equation (1) and (2). As the object position is known, surveyor robot is faced to its position by changing angular velocity. When the robot arrived at given distance from target object (60% of distance sensor S_5 reading) as shown in Fig. 3.4(a). The surveyor robot will stop and turn left to make it position in same direction with the object side. Then robot moves clockwise while keeping the distance by using sensor S_0 and S_2 as shown in Fig. 3.4(b). Moreover, the distance is measured by using sensor S_0. Start point of surrounding is recorded that will be used as stop point.

3.5 Estimating object shape and size

The recorded distance data are converted to the coordinate and processed to get convex hull by using Graham Scan algorithm [86]. The first step in this algorithm is to find the point with the lowest y-coordinate on the world coordinate system $\sum w$. If the lowest y-coordinate exists in more than one point in the set, the point with the lowest x-coordinate out of the candidates should be chosen as P_0. This step takes Q_n, where n is the number of points in question.

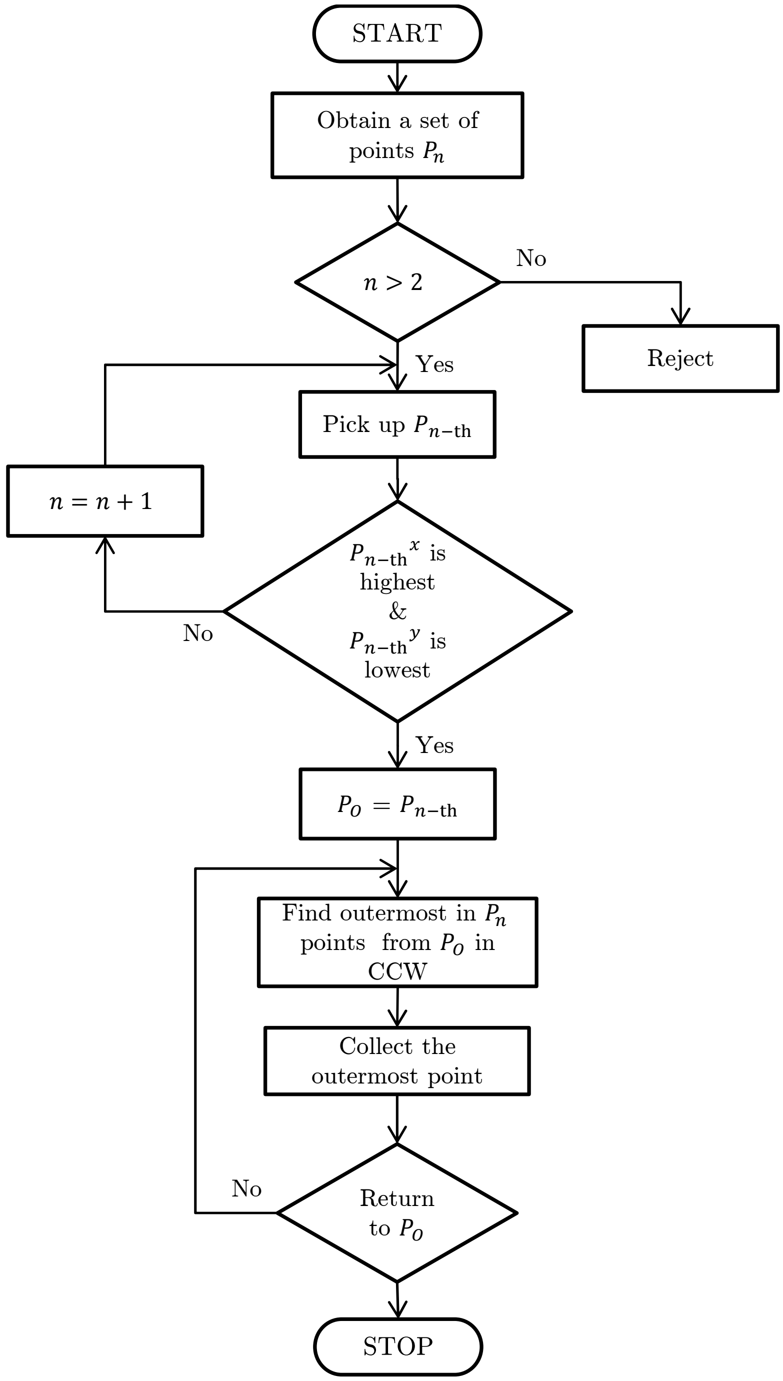


Figure 3.5: Flow chart of graham scan algorithm

Next, sort the remaining points of Q lexicographically by polar angle, measured in radians. Interior points on the ray cannot be convex hull points and remove these points during sort. Once the points are sorted, they are connected in counterclockwise order with respect to the anchor point P_0 as shown in Fig. 3.6.

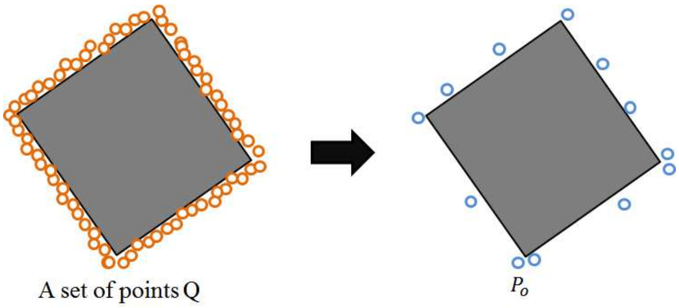


Figure 3.6: Points processed with Graham Scan algorithm

3.6 Determining push points

Convex hull is a set of recorded points which is simplified But it may contains unnecessary points. For example, a rectangular object consists of four corners and four straight lines. In rectangular convex hull, some points will appear between corner points and it is not necessary as shown in Fig. 3.6. Thus, such points must be eliminated to simplify next process. To eliminate these points, simple corner detection method is used. The method calculates the angle between two lines that composed by three sequences of points. If at the bottom corner of Fig. 6 is point Q_n, then point Q_{n+1} and Q_{n+2} are next points at clockwise direction. And then, the angle of first line (point Q_n and Q_{n+1}) to second line (Q_{n+1} and Q_{n+2}) are calculated. If the angle are larger or equal than minimum angle θ_e, point Q_{n+1} is considered as a corner. θ_e is angle threshold for detecting corner.

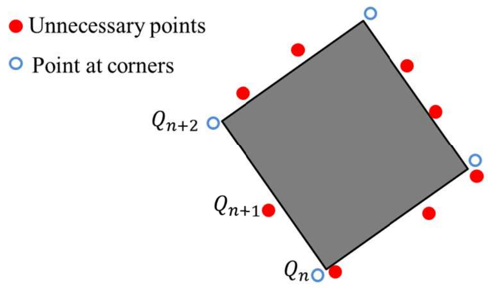


Figure 3.7: Points of convex hull

After corner detection is finished, a set of points T_n that consist of corner points is obtained. However, push points are not in corner points because it has a small contact surface. Therefore, a position between corners is chosen as the push point. These points can be calculated by using average of T_n and T_{n+1}. Push points of the rectangular object are shown as the black circle in Fig. 7. The push point for the initial push is selected among them if its location is in the behind of the object.

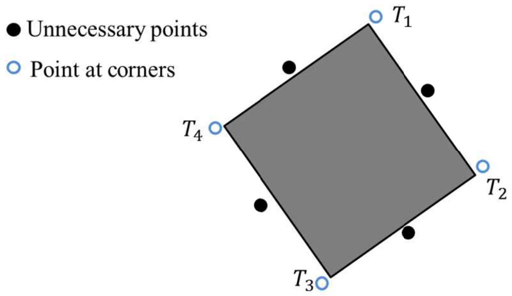


Figure 3.8: Push points of rectangular object

3.7 Conveyance process

Object conveyance by multiple mobile robots is carried out by simple push. The surveyor robot performs initial push in estimated push point. During conveyance, surveyor robot motion is controlled to be in same direction of the sub-goal and object. If the surveyor robot can push the object to pass the sub-goal within 8 second, another robot is not required. If the surveyor robot cannot push by itself, another robot will come to help. However, three robots are also used from beginning of push. The first robot is a pusher which is required to push the object. And other two robots are aligners that navigate the object on the desired trajectory.

In order to control the formation these three robots, virtual structure approach is used. And for controlling each individual robot, the simple sliding mode control is implemented. The flowchart of the sliding mode control and virtual approach are illustrated in Figs. 3.8 and 3.9.

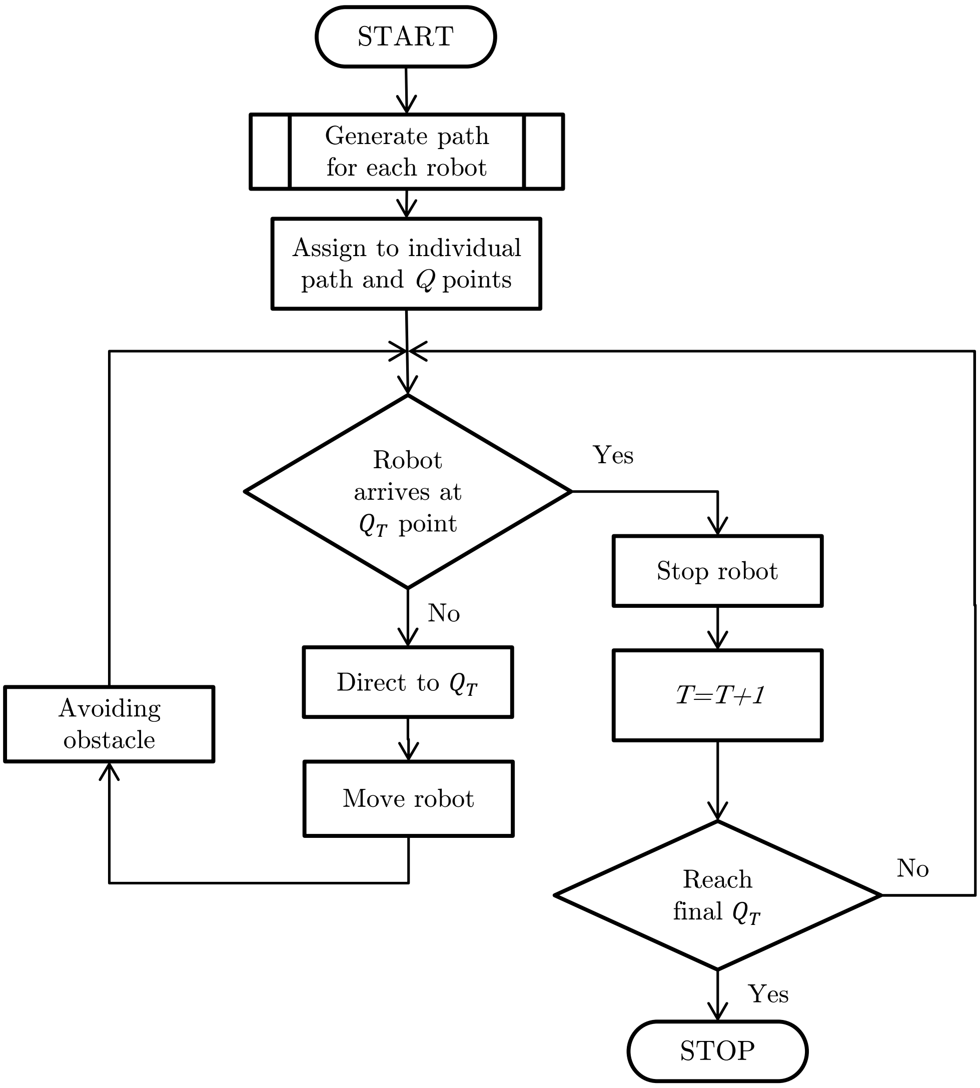


Figure 3.9: Flowchart of developed sliding mode control

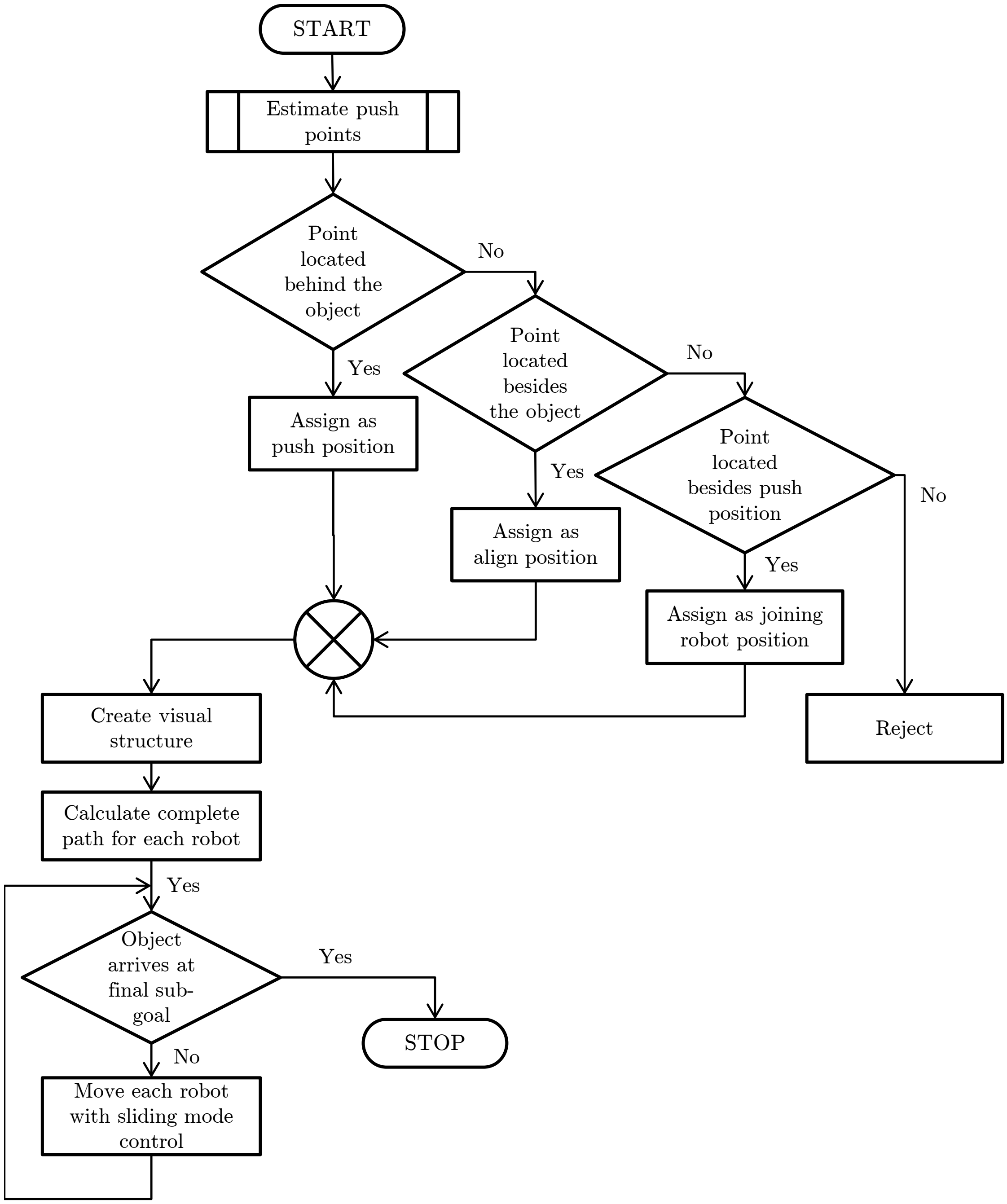


Figure 3.10: Flowchart of developed virtual structure

CHAPTER 4

Simulation Results

A simulation system is developed using python 2.7 with physical dynamic module in order to make robot motion is similar to the real system. Simulation platform consists of an obstacle free workspace, an object, and five mobile robots. The object shape might be several of regular shape such as rectangular, pentagonal, hexagonal, heptagonal and octagonal shape. Irregular objects are used in the simulation to demonstrate the proposed algorithm. Furthermore, each robot is located randomly thus it may appear different position on each result figures.

4.1 Regular polygon object

Approaching step is shown in Fig. 4.1 Robot (surveyor robot) departs from random start point to the object while avoiding collision with other robot. The robot stops and turn left to align the direction parallel to nearest object side after arrived at 60% of distance sensor reading (7cm for actual scale). Then, the robot moves one cycle to surround the object in clockwise as shown in Fig. 4.2. During surrounding, the robot measures the distance and converts it into a coordinate and record. The coordinates are illustrated using gray circle alongside the object.

After the robot rotated one cycle along the object and recorded the distance, collected data is processed using graham scan algorithm to make convex hull which consists of selected points. The several unnecessary points are eliminated by using corner detection. Fig. 4.2 shows a rectangular object with surrounded convex hull points (gray circle). At the corners, there are four black circles which the points selected from convex hull. Then, red circles are push points that located between the corners as shown in Fig. 4.3.

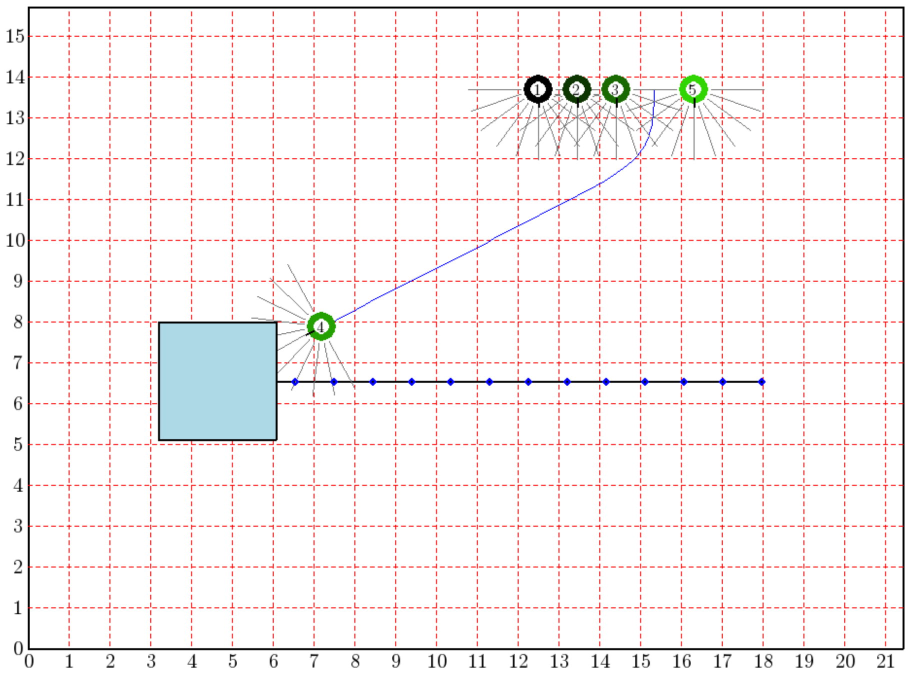


Figure 4.1: Approaching rectangular object

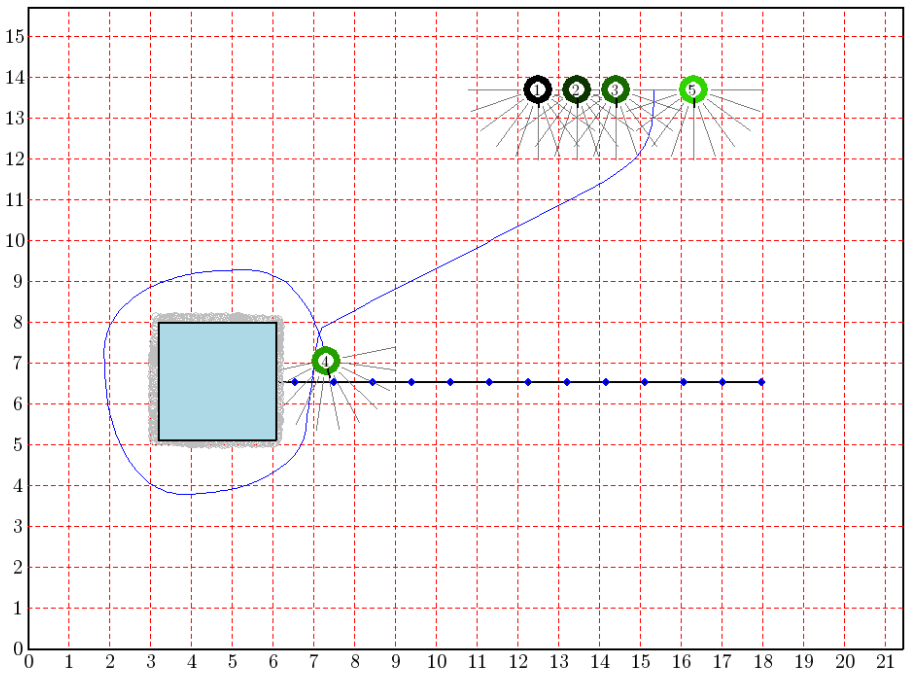


Figure 4.2: Surrounding and measuring object

Figure 4.4 shows that the robot is getting close to the selected push point as a push position. For rectangular object, push position can be estimated in each straight side. In the Fig. 4.3, pentagonal to octagonal object are used and also, push positions are also able to be estimated. The robots are numbered from 1 to 5 as their identity.

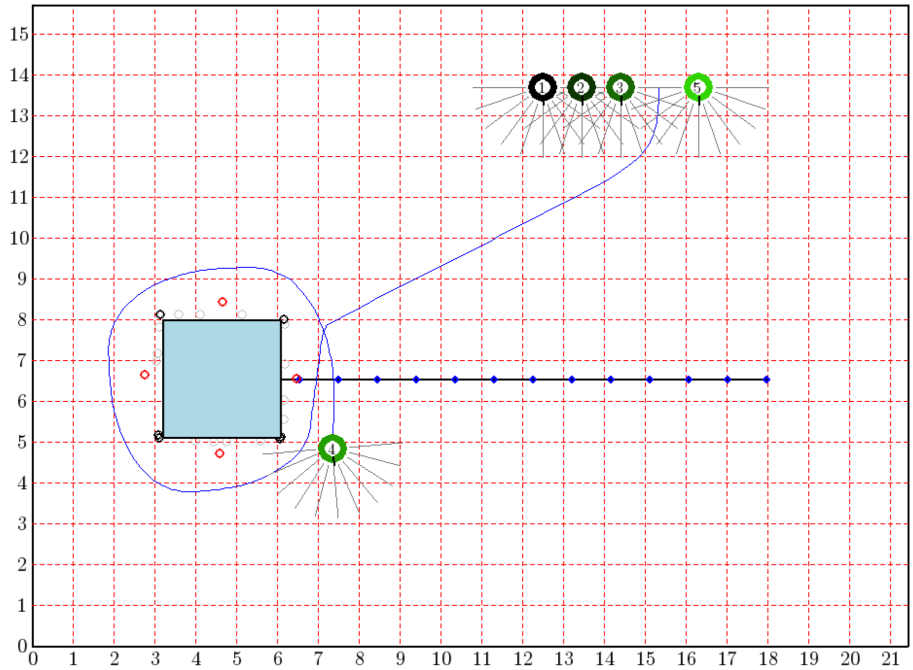


Figure 4.3: Corner and push point estimation

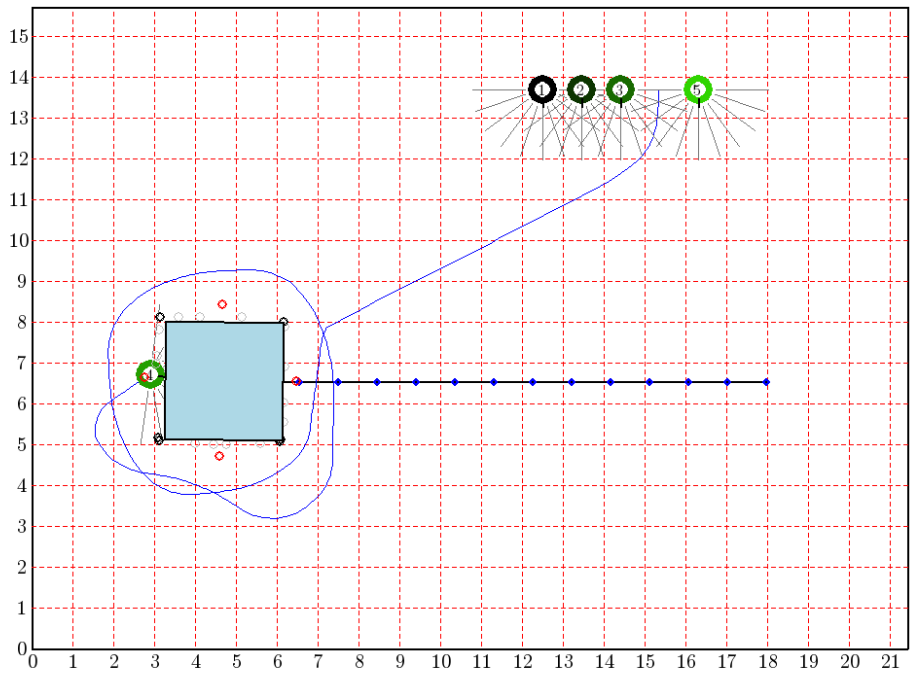


Figure 4.4: Getting close to the object

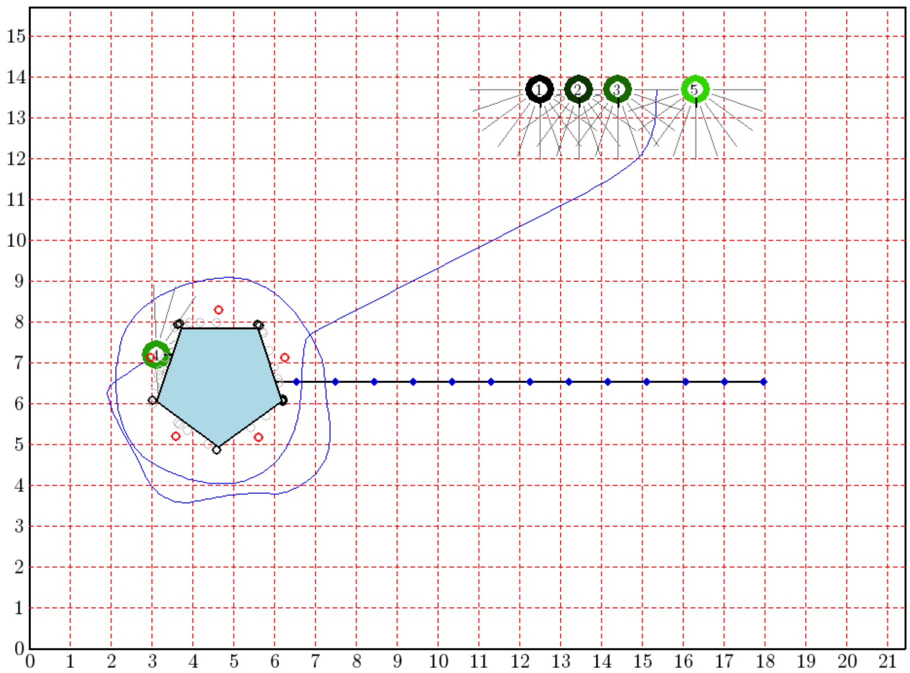


Figure 4.5: Push points of pentagonal object

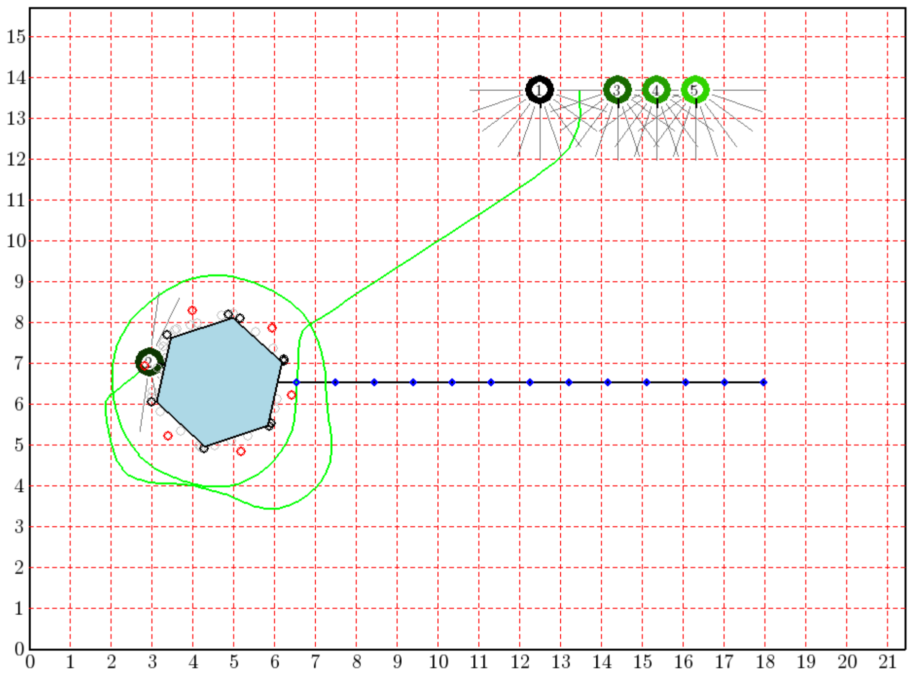


Figure 4.6: Push point of hexagonal object

We also examine proposed algorithm in several regular polygon objects from pentagonal to octagonal. Results show that the push points can be estimated. All used object in this simulation are assumed as solid object with a particular height so the distance sensor can detect their existence.

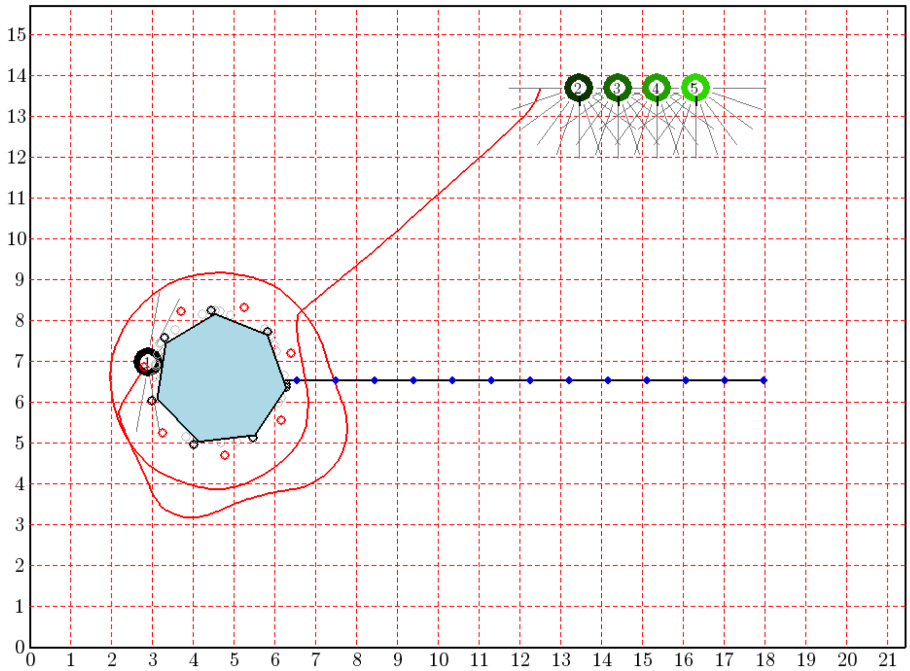


Figure 4.7: Push point of hexagonal object

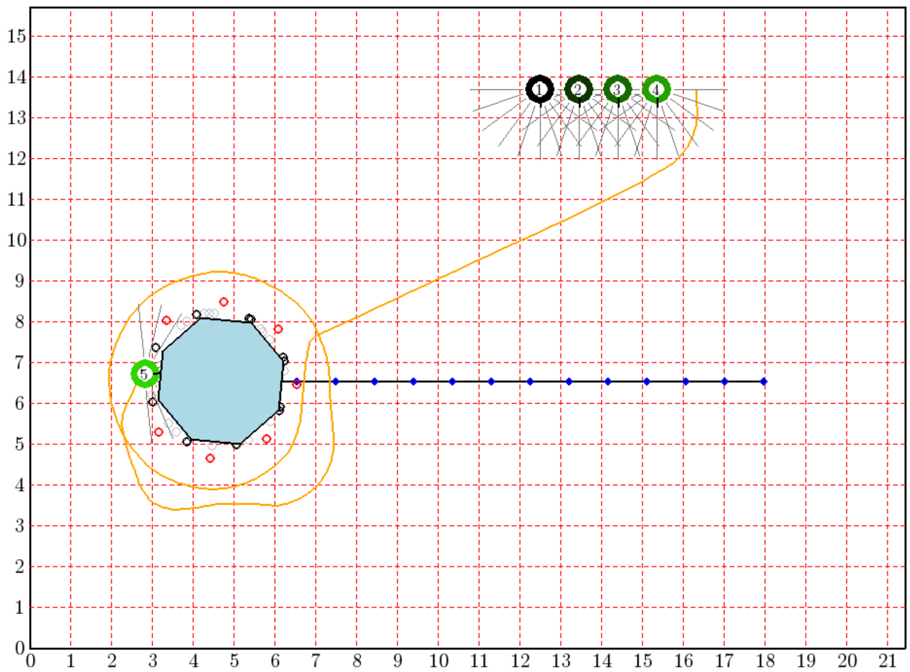


Figure 4.8: Push point of octagonal object

4.2 Irregular shaped object

The step from approaching to surrounding of irregular shape is similar to regular object. Surveyor robot departs from random start point to the object and arrived at specified distance, the robot stops and turns left to align the direction parallel to the nearest object side. Then, robot moves one revolution to surround the object in clockwise as shown in Figs. 4.9 to 4.10. During surrounding, robot measures the distance and converts it into a coordinate and record. The coordinates are illustrated using gray circle alongside the object.

The step of obtaining convex hull and push point are shown in Fig. 4.10. This irregular shaped object has three different sides. These are straight, curved and cornered sides. However, the algorithm can address this object and give the result as expected. Another irregular shaped is also used to demonstrate the algorithm as shown in Figs. 4.11 to 4.13. In the figure 4.10, the step of obtaining push point where the surveyor robot needs to come for making an initial push is shown. Next simulation result is the conveyance process with minimum robot number as the result of this algorithm.

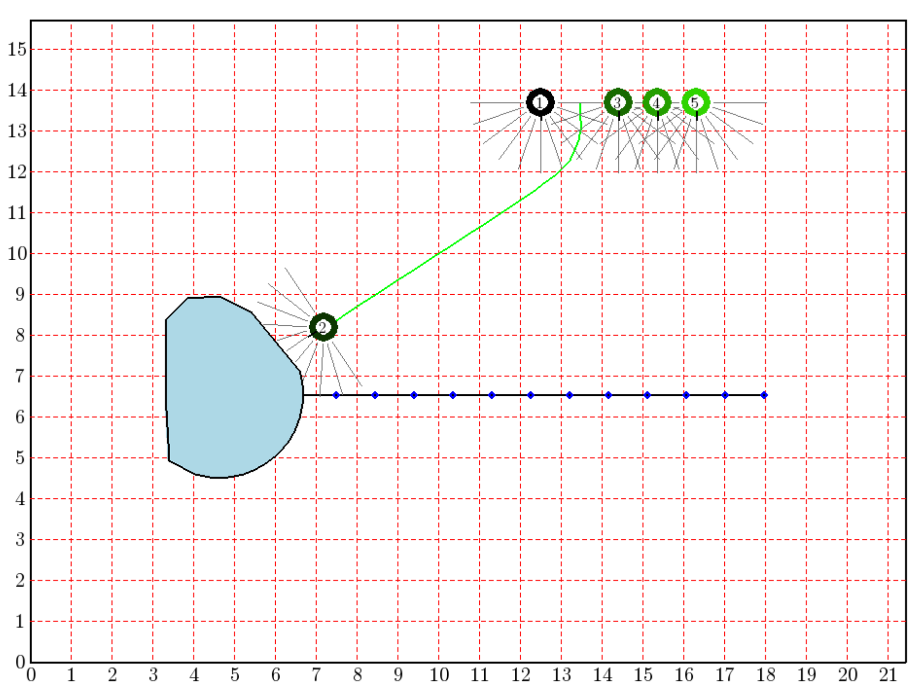


Figure 4.9: Approaching of an irregular shape object

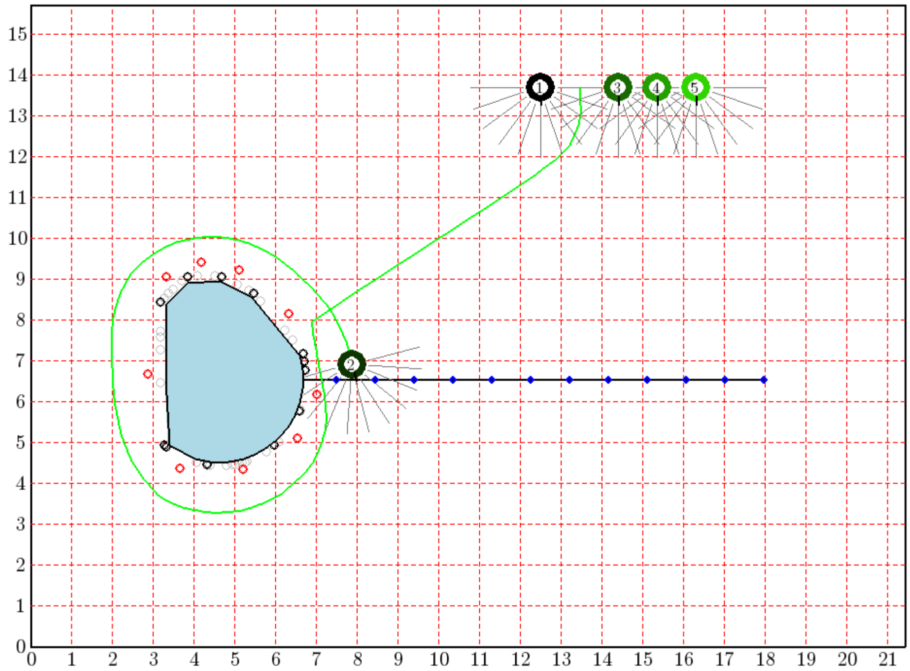


Figure 4.10: Obtaining push points of irregular shape object

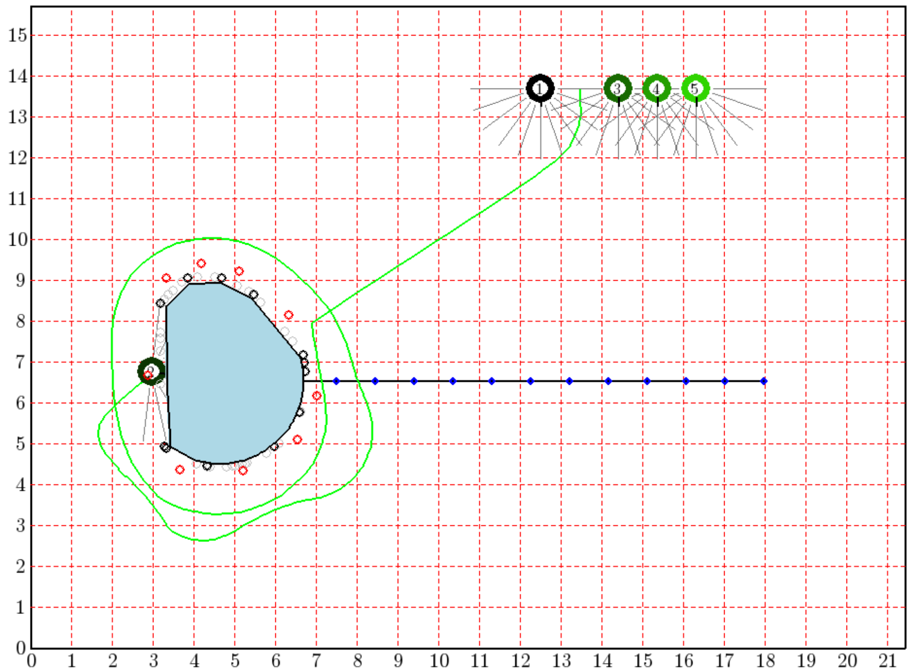


Figure 4.11: Surveyor robot make initial push

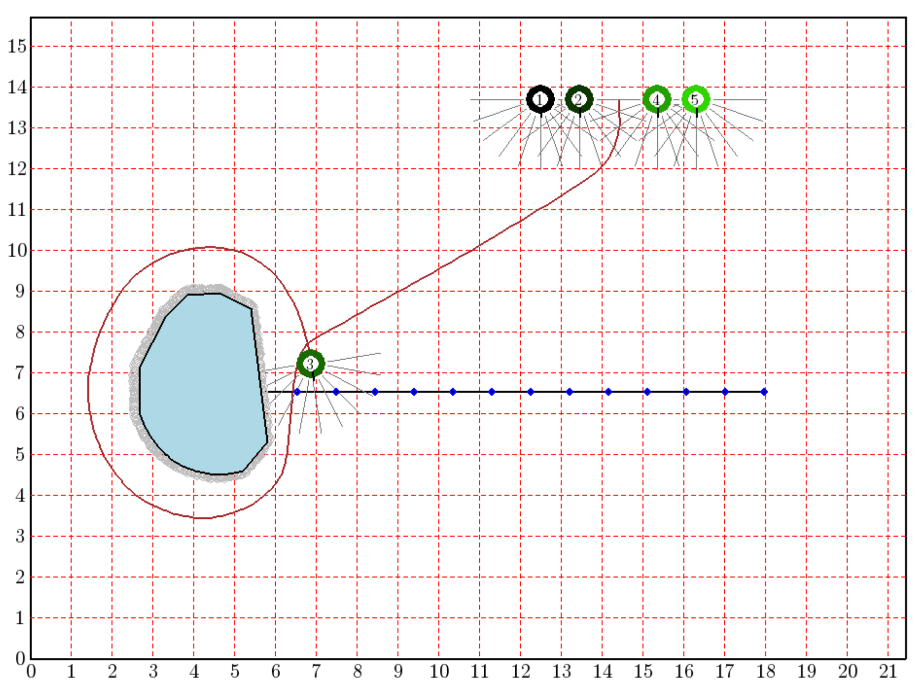


Figure 4.12: Result of another irregular shape object

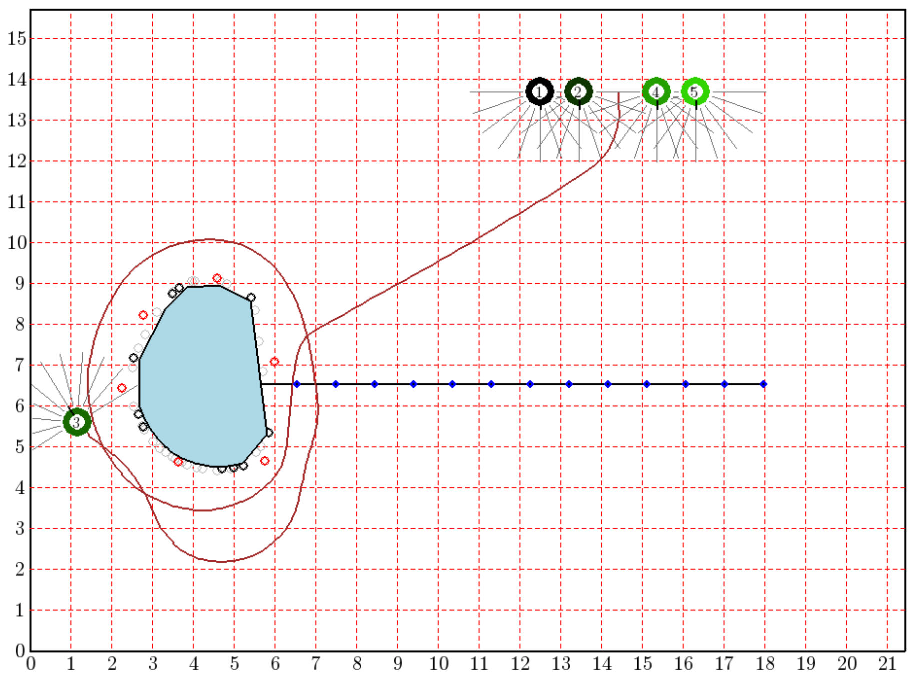


Figure 4.13: Obtaining push point of another irregular shape object

4.3 Object conveyance

In this simulation, rectangle object with two weight option is used to examine proposed algorithm. The weight can be selected to 1kg and 3kg (simulation scale). Robot team consists of one pusher robot and two aligner robots which are located in behind, right and left side of the object. This position is obtained by surveyor robot in push points estimation phase. The used trajectories are one straight line and three combinational straight lines. Therefore, there are four results in this object conveyance phase. Figures 4.14 to 4.17 show the conveyance process of 1kg rectangle object on the one straight line trajectory.

At the beginning, surveyor robot (number 1) approaches, surround and measure the object using distance sensor to obtain the object shape as shown in Fig. 4.14. The unnecessary points are eliminated to get corner and push point. Then the robot number 1 comes to push point located behind the object. This object conveyance uses two additional robots (number 4 and 5) to align the object direction on the desired trajectory. Figure 4.17 shows the conveyance result from start to final point.

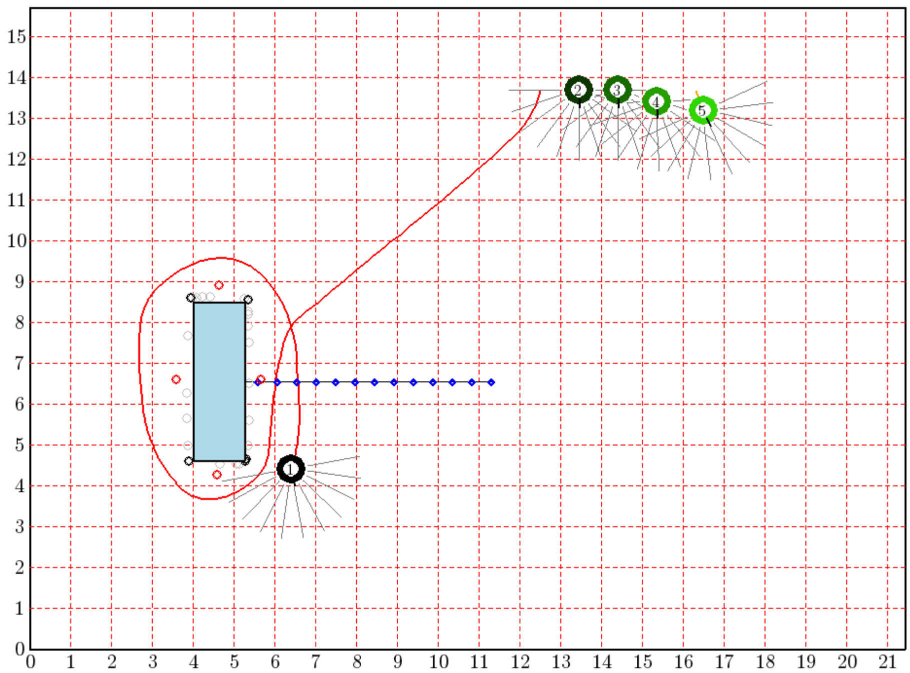


Figure 4.14: Simulation result of second robot join

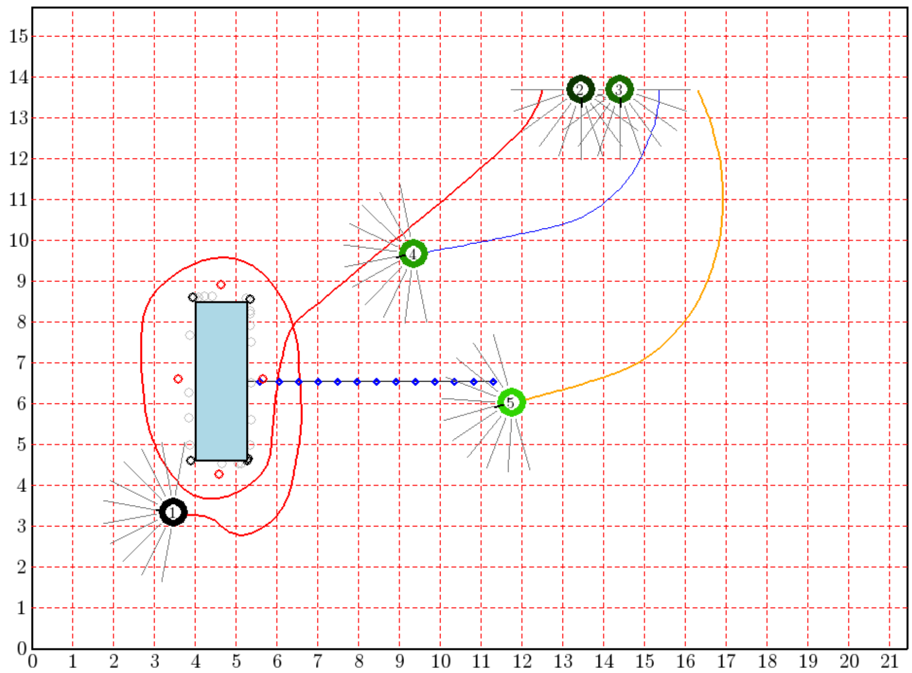


Figure 4.15: Simulation result of second and third robot join

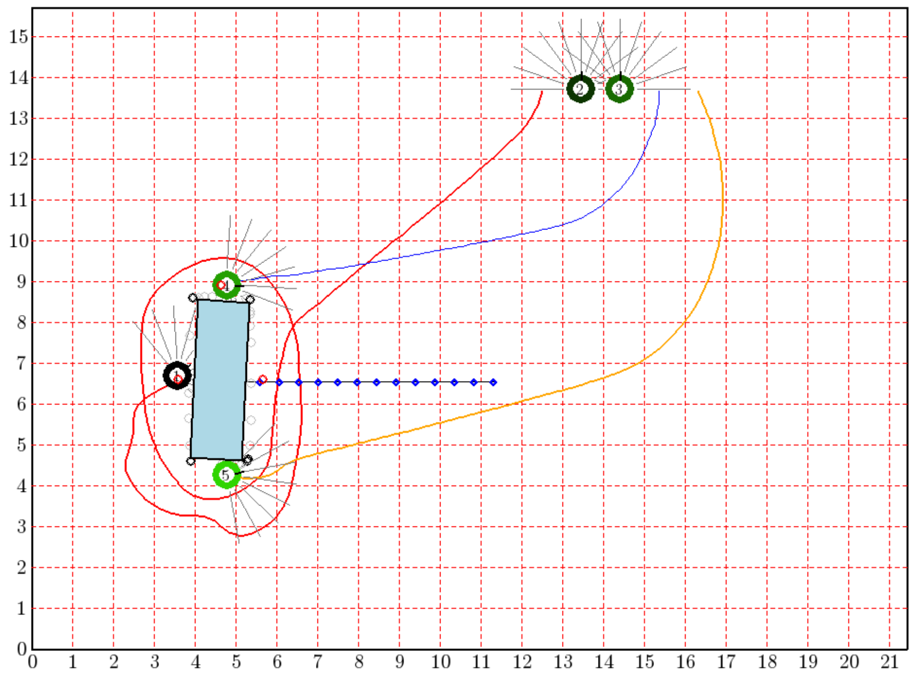


Figure 4.16: Three robots make a conveyance formation

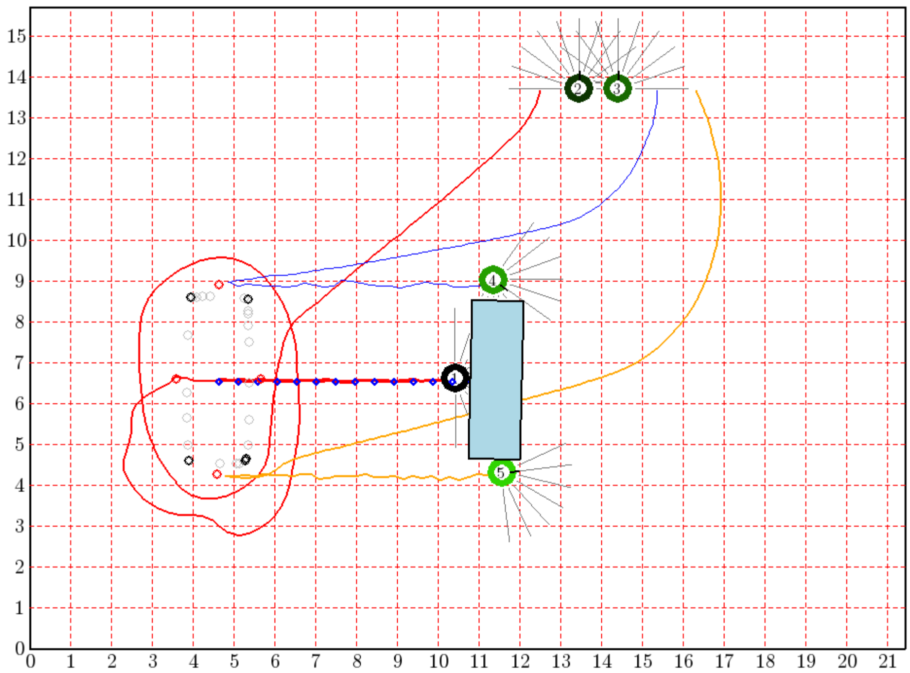


Figure 4.17: Simulation result of one robot moves 1kg rectangle object

In the Figures 4.18 to 4.21, the conveyance processes of 3kg rectangle object are shown. This object conveyance is carried out by five robots which the first r robot pushes the object in given distance within required time. As shown in Fig. 5.18, the desired trajectory consists of 15 sub goals which are indicated by blue circle on the black line. Other two robots are used to navigate the object on the desired trajectory. At that time, given mission includes a limitation of conveyance speed which the object are needed to be moved in 8 seconds for each sub-goal. This value is known by considering simulation environment such as robot and object weight, friction, and pixel to actual distance ratio. Therefore, if the surveyor robot cannot move the object within eight second, the object is considered as heavy object.

In Fig. 4.19, the surveyor robot experiences difficult movement because the object weight is 3kg and considered as a heavy object. Therefore, another two robots comes and join to support the first. Team member increment is decided by measuring movement time and elapsed distance. Next joining robots is used the team if the performance less than the required setting value.

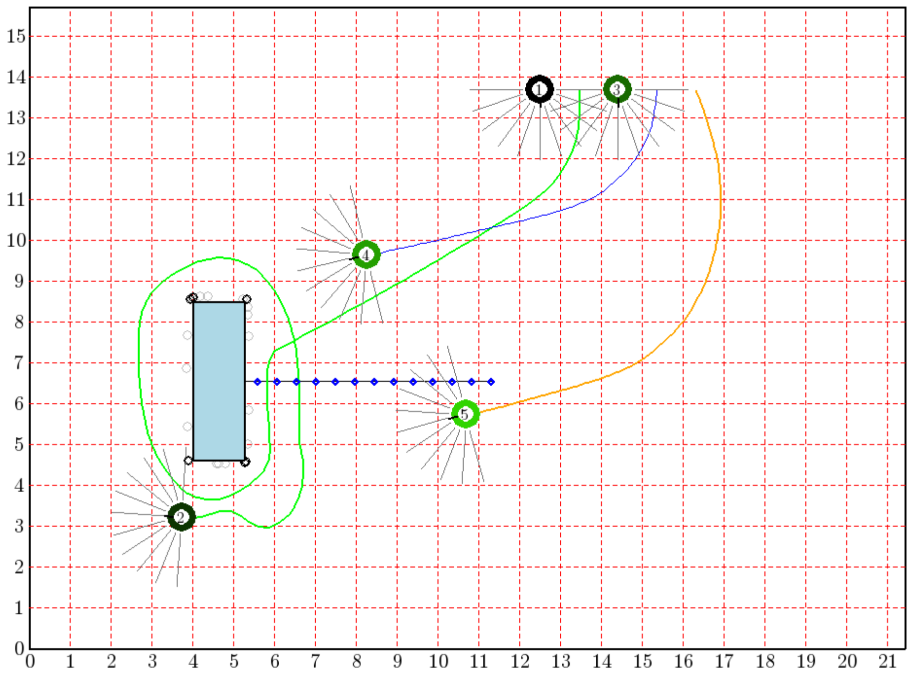


Figure 4.18: Simulation result of second and third robot join in 3kg rectangle object conveyance

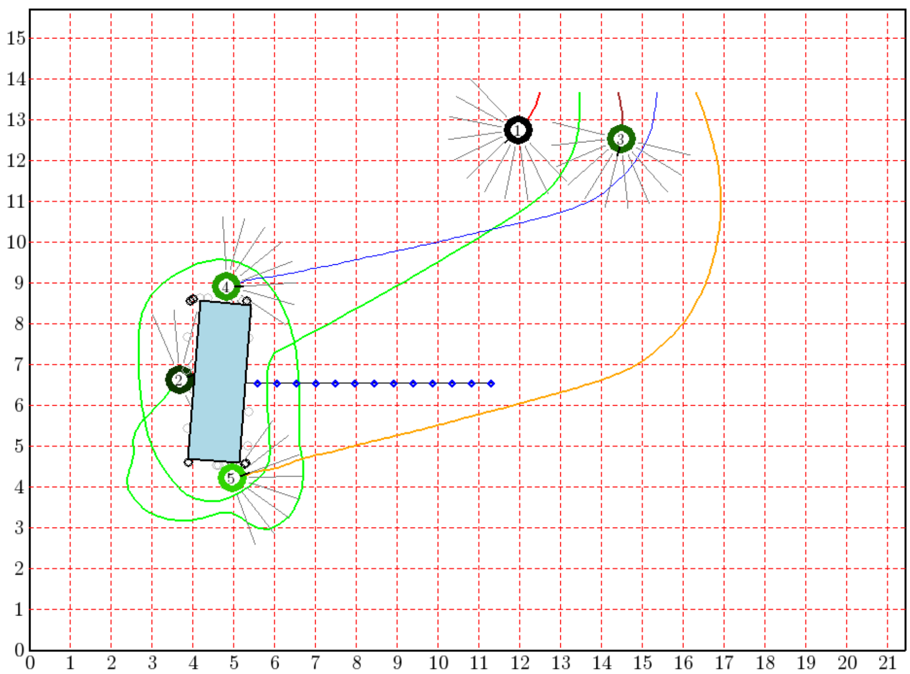


Figure 4.19: Simulation result of second robot join

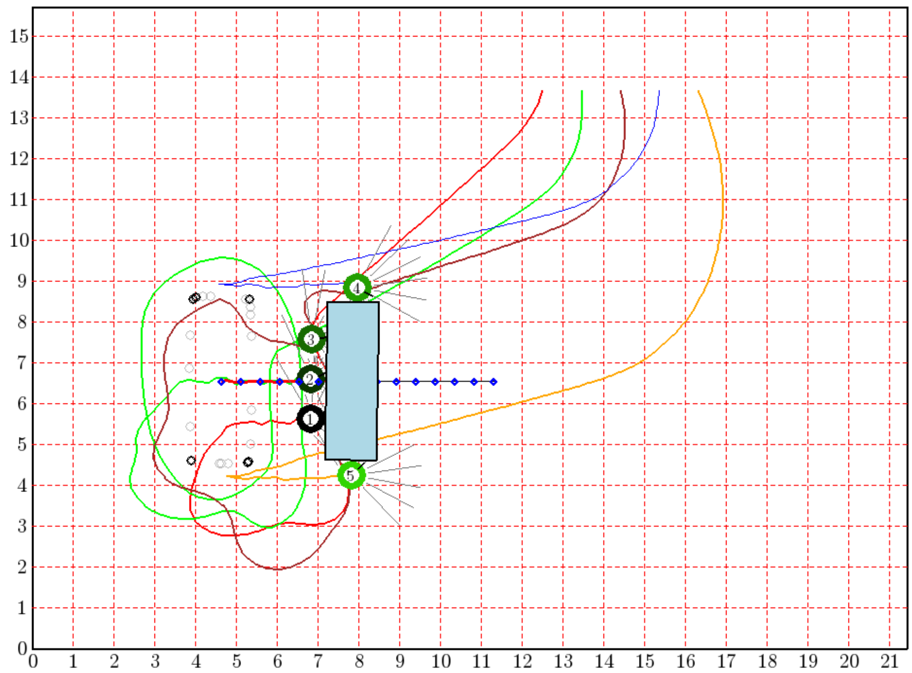


Figure 4.20: Simulation result of second robot join

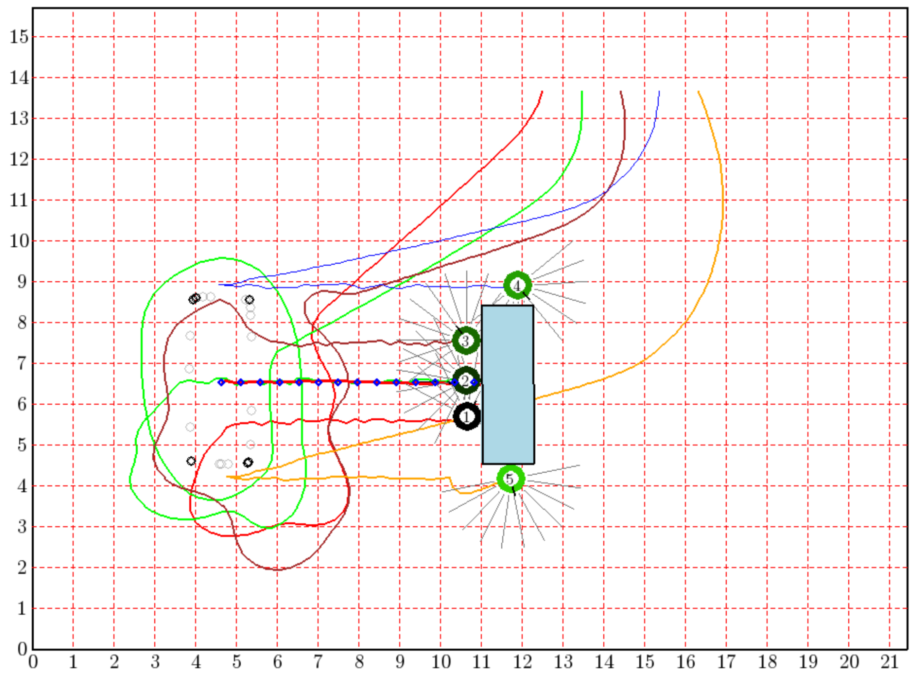


Figure 4.21: Simulation result of second robot join

Object conveyance by three robots on the combinational three straight lines is shown in Figs. 4.22 to 4.29. As the previous simulation, the first robot is a surveyor (robot number 2) and other two robots are used to navigate object on the desired track. In Figure 4.22 to 4.25, conveyance processes are illustrated similarly to previous simulation. Surveyor robot estimates push position as shown in Fig. 4.22. The red circles are the estimated push positions.

The movement of three robots is cooperatively carried out with visual structure approach. The visual structure is created after the surveyor robot estimated the push positions. In order to move the object on the desired trajectory, the team is divided as a pusher and aligner. The pusher robot is required to push the object from appropriate position. The aligner robot is required to navigate the object on the trajectory so the object can be moved as expected. Figures 4.26 and 4.27 show the object conveyance on the desired trajectory where the sub-goal orientation is changed. The pusher robot is changed from robot number 2 to robot number 3. The robot 2 and 4 become the aligner. The movement on the non-straight line is carried out without keeping the object orientation continuously perpendicular to desired trajectory.

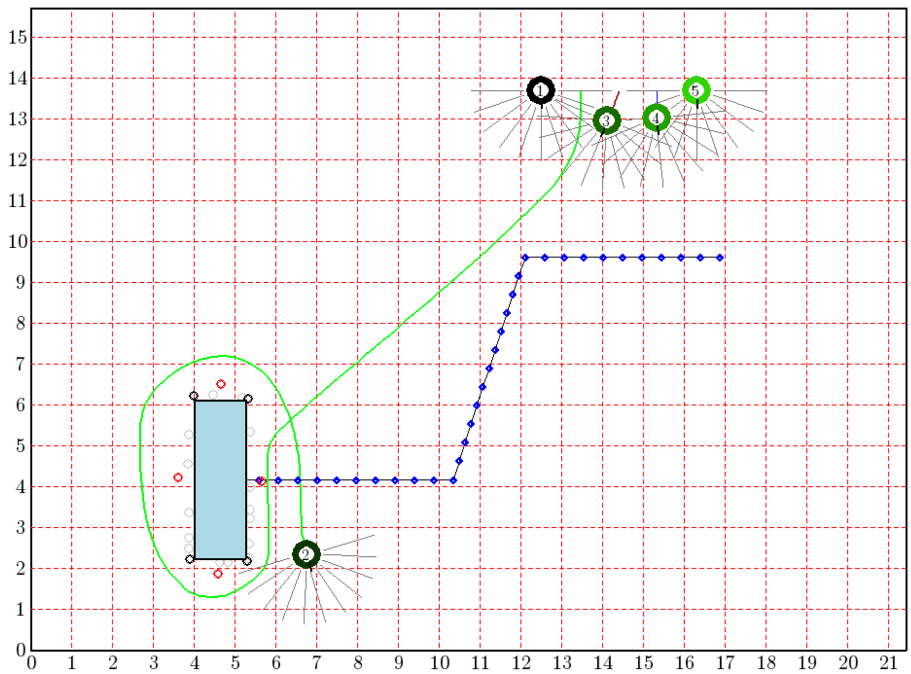


Figure 4.22: Simulation with three combinational straight lines trajectory

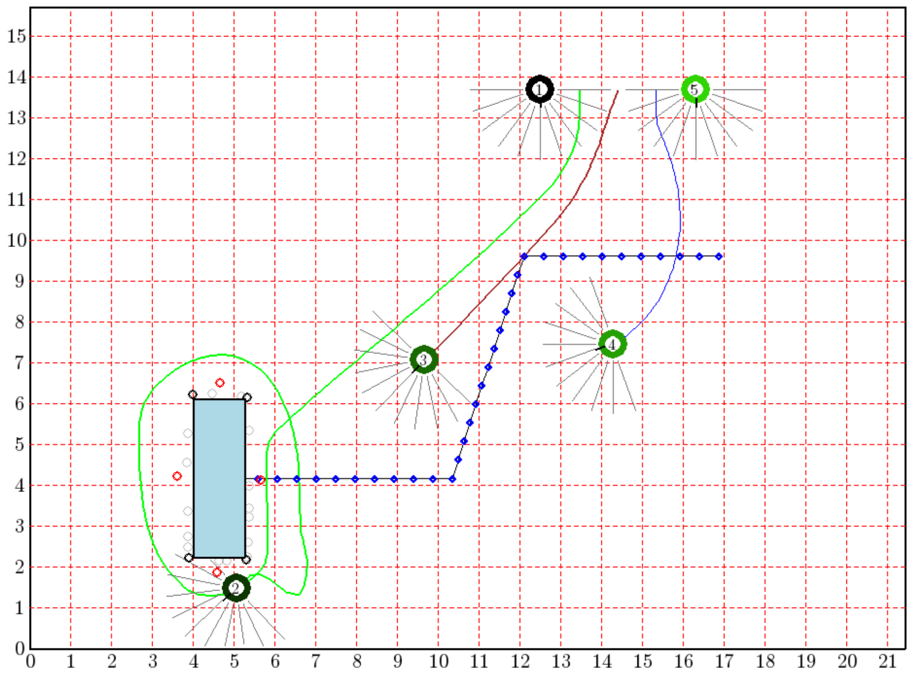


Figure 4.23: The surveyor robot comes to push position

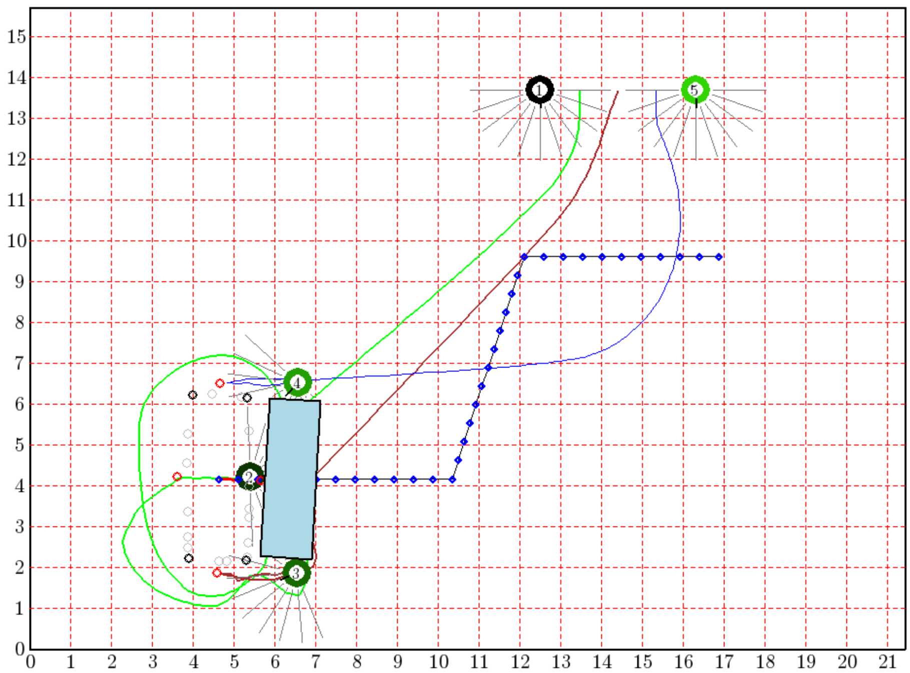


Figure 4.24: Aligner robot comes to the position

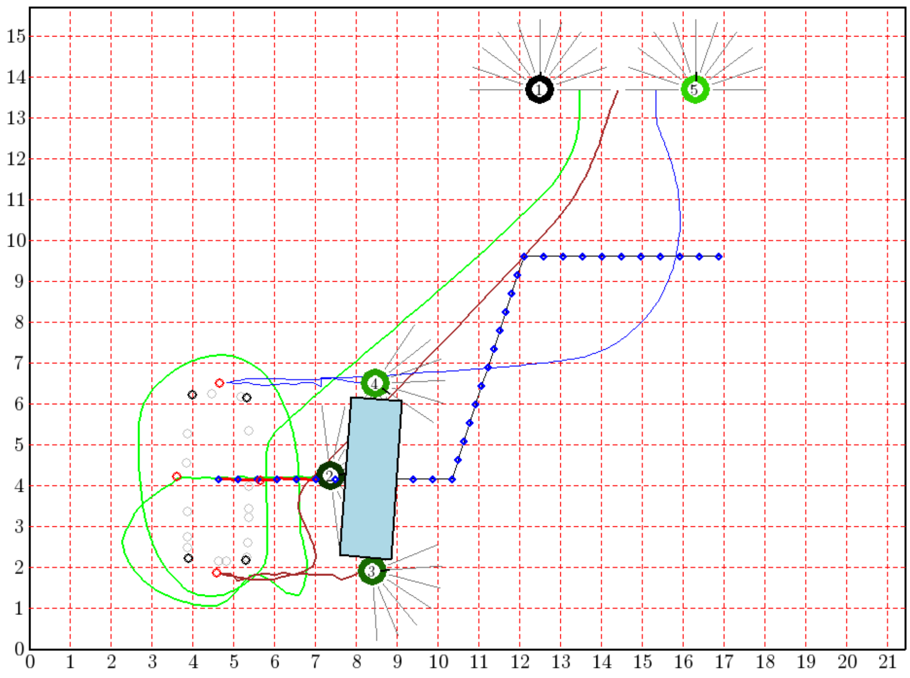


Figure 4.25: Three robots push move the object

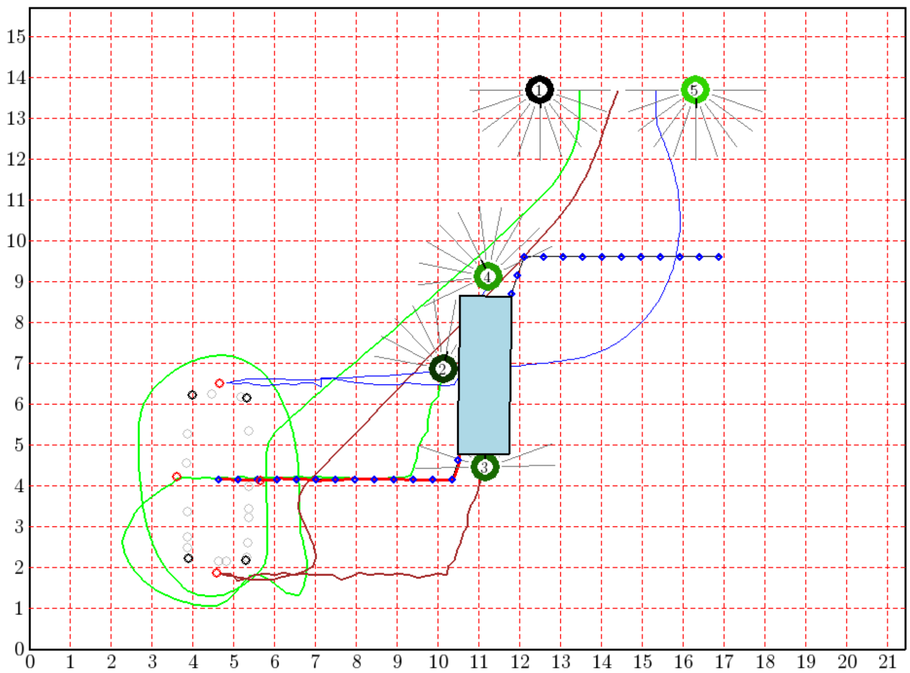


Figure 4.26: Pusher to aligner changes (vice-vesra)

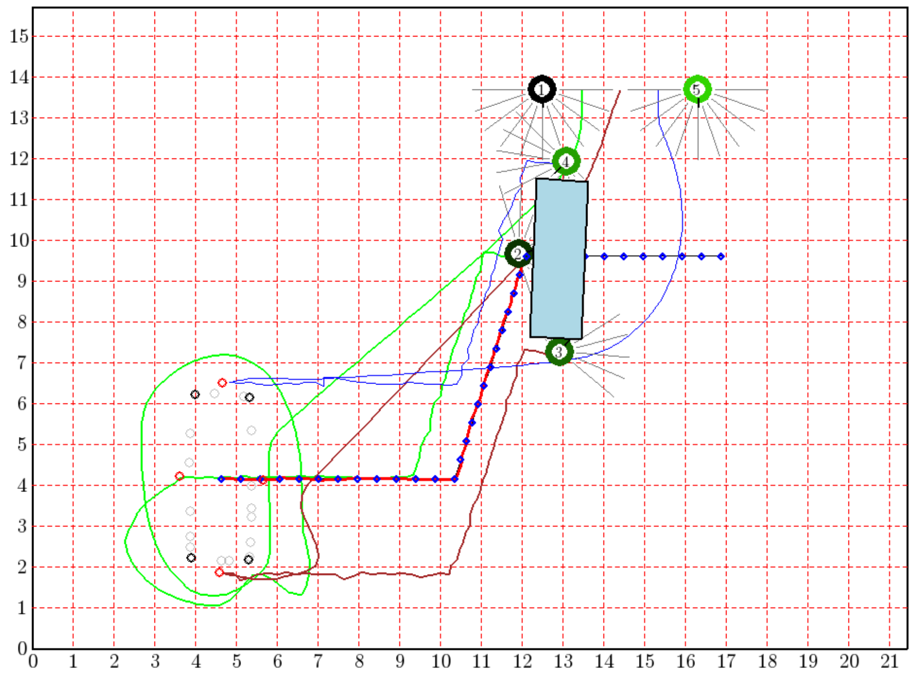


Figure 4.27: Pusher to aligner changes (vice-vesra)

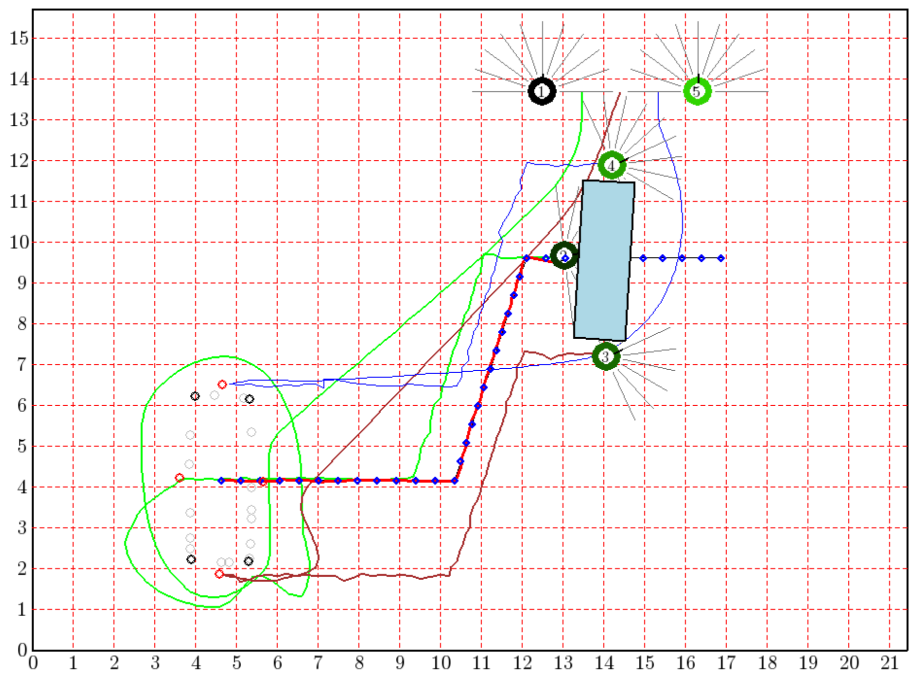


Figure 4.28: The object trajectory (red line) fit to desired trajectory (black line with blue points)

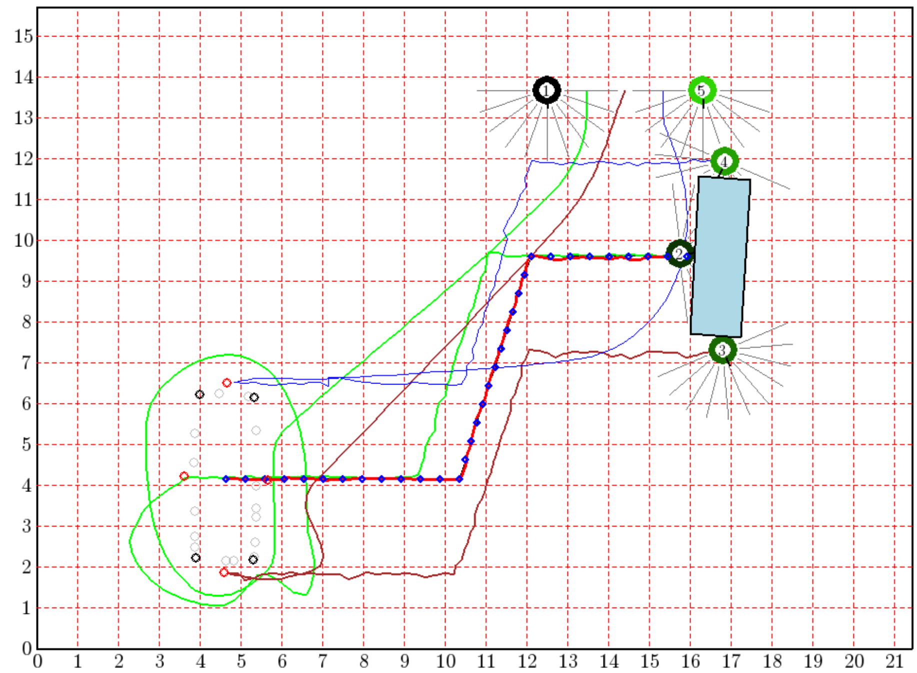


Figure 4.29: Move the object to final sub-goal

The object weight is changed from 1kg to 3kg thus the other two robots join to help the surveyor robot. Result of this simulation is shown in Fig. 4.30. The object is successfully transported from start to final sub-goal.

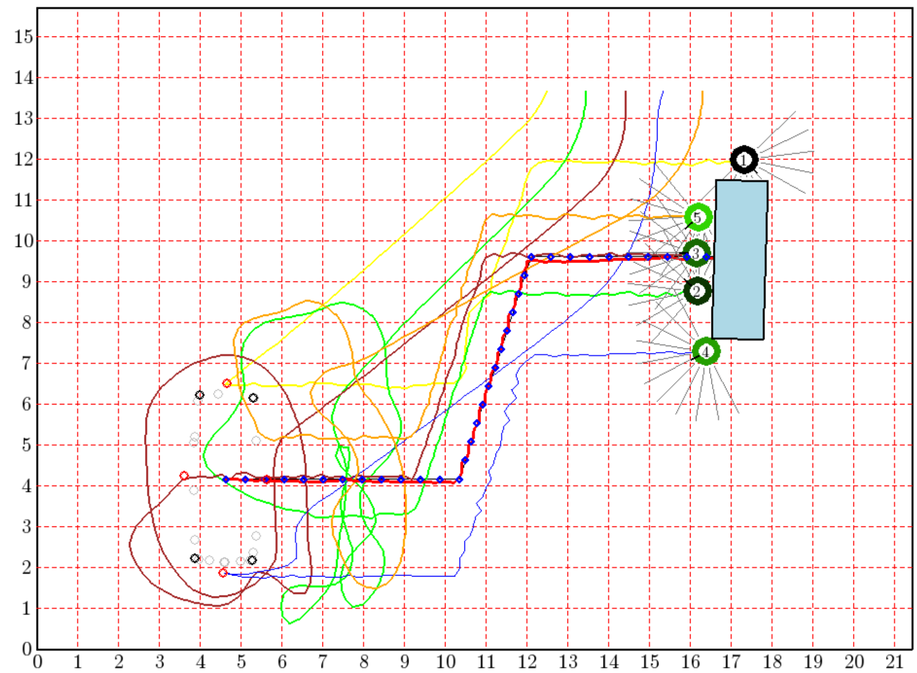


Figure 4.30: Move the object to final sub-goal

CHAPTER 5

Experimental Results

5.1 Developed experimental system

In this system, we used the overhead positioning system for tracking four mobile robots as shown in Fig. 4.1. The host PC is connected to an USB camera for obtaining image information. The obtained image is processed by using developed software to get each robot orientation and position that is indicated blue triangle marker on the top of the robot. For sending command and obtaining sensor data from the robot, XBee wireless module is used.

The camera generates 1280x720 of the image with 30 frames per second for capturing 200x150 cm workspace. This image is processed by using OPENCV, FFMPEG in python programming language. Inside of image processing, there are color filtering, contour detection, and triangle detection function to get robot position. Because of the noisy position data are obtained, the KALMAN filter is used to stabilize. In addition, a special function is used to keep each robot position stay at their original positions everywhere they move.

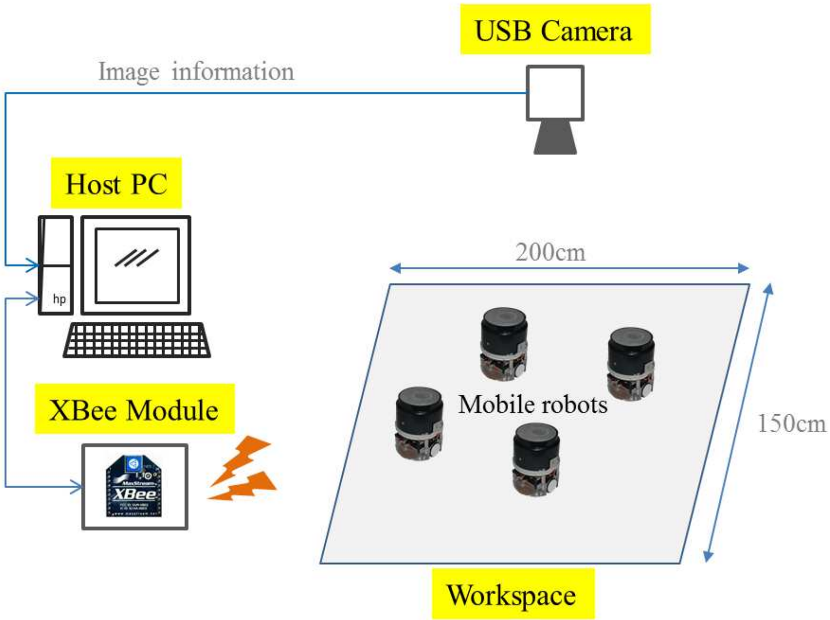
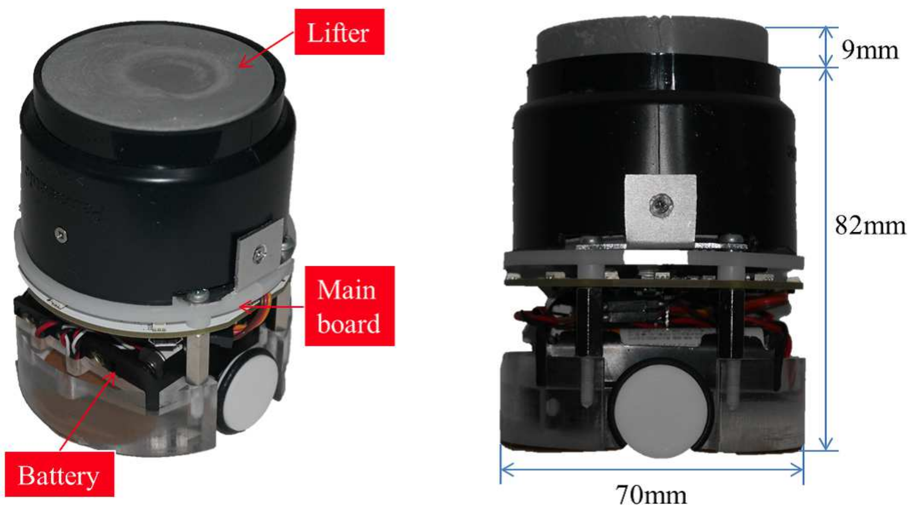


Figure 5.1: Developed experimental system

5.1.1. Developed mobile robot

Figure 5.2 shows the appearance of the developed mobile robot that is upgraded from previous version. The new features of this robot are better mainboard and vertical lifter that can be used for moving an object with lifting mechanism.



(a) Overview (b) Side view

Figure 5.2: Developed mobile robot

Detail specification of the mobile robot is shown in Table 5.1.

Table 5.1: Specification of developed mobile robot

Robot size	Description
Height	82-91mm
Diameter	70 mm
Weight	250 gram

Mainboard	Description
Processor	STM32F407
Clock	168MHz
I/O	Analog, digital
Indicator	8-Ring RGB LED
Storage	SD Card memory

Motor	Description
Type	GWS PICO/STD/F
Max Speed	9.4 cm/s

XBEE Module	Description
Frequency	2.4 GHz
Baudrate	38400

Sensor	Description
Distance	5 x GP2Y0E02
IMU	MPU9250

In order to implement the developed algorithm, distance sensor and marker are needed to be included in the mobile robot.

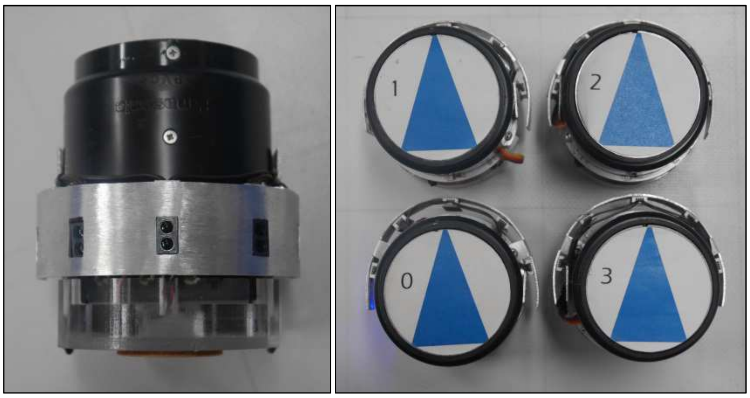


Figure 5.3: Installed distance sensors and markers

5.1.2. Tracking system

As the position information of each robot is required, a local positioning system is needed. In this study, positioning system based on image information obtained by using overhead camera is used. Developed software is also used to process the image from overhead camera to several required information. And to simplify the tracking process, identical markers are located on the top of each robot as shown in Fig. 5.3. In addition, each robot has an ID number from 0 to n-robot. In this experiment, there are 4 robots and their ID numbers are defined from 0 to 3.

The position tracking system works by recognizing both robot position and ID number to get correct information of each robot. The software identifies the markers from bottom right to top left and marks the robot ID from 0 to 3 sequentially. However, actual robot ID may not same to the software identification. Therefore, ID swap feature is included in the software function.

5.1.3. Object target

Proposed algorithm may adapt to several regular and irregular objects as demonstrated in the simulation results. In this experimental work, a rectangular object with 90x245x335mm size and 125g weight as shown in Fig. 5.4 is used to verify the simulation result. Afterward, a blue colored circular marker is placed on the top of the object for camera tracking. Even though the marker color is identic to the robot marker color, object marker is enlarged than the robot marker to distinguish them. The use of identical color for all objects simplifies object tracking process of the positioning system.

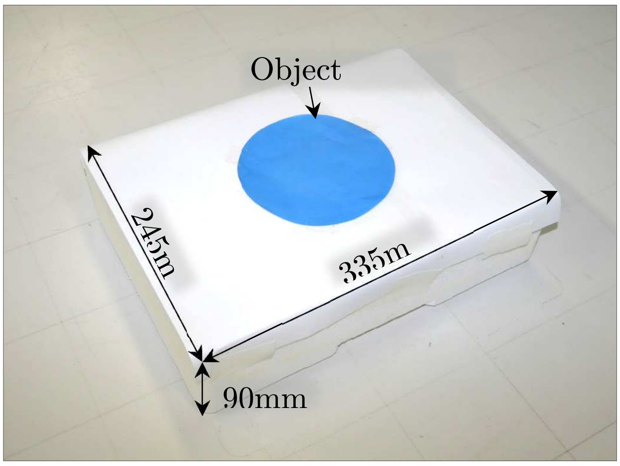


Figure 5.4: Installed distance sensors and markers

5.2 Results of object push points estimation

The experiments of proposed algorithm are divided into two sections. They are the object push points estimation and object conveyance. The object push points experiment is carried out from the beginning of surveyor robot approaches the object until it arrives at its correct push position. It is shown in Figs. 5.5-5.7. The first step is approaching when the surveyor robot is departed from a random selection of existing robots to conveyance object position. After the surveyor robot gets close about 10cm, the surrounding and coordinates measurement are started.

The measured object coordinates are simultaneously stored and indicated with black circle surrounding the object. It is shown that the measurement is successfully done. Therefore, after the surveyor robot surrounds the object in one clockwise rotation, the collected coordinate data is processed to be a convex hull. From a convex hull, the corners detection algorithm is used to eliminate several non-high narrowed points. At last, the push points are obtained a median point of two corner points. The result of push point estimation for the rectangular object is shown in Fig. 5.7. Detail of process is illustrated in Fig. 5.8. The cyan dost are the measured coordinates data, blue dots are the convex hull, red dots are the corners and the green dots are the push points.

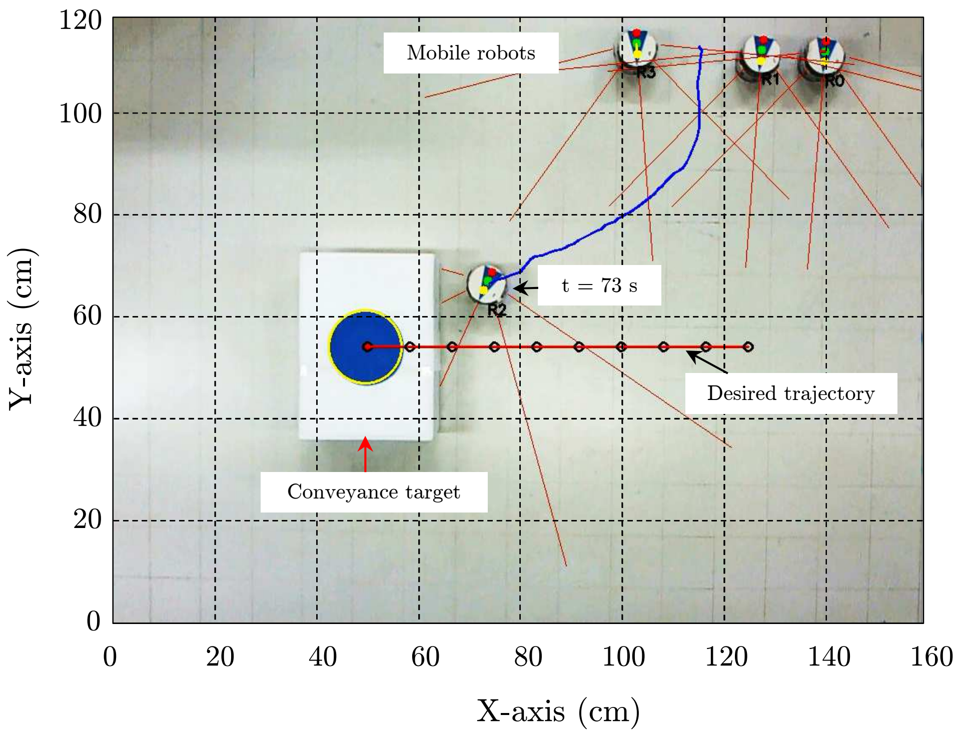


Figure 5.5: Surveyor robot approaches

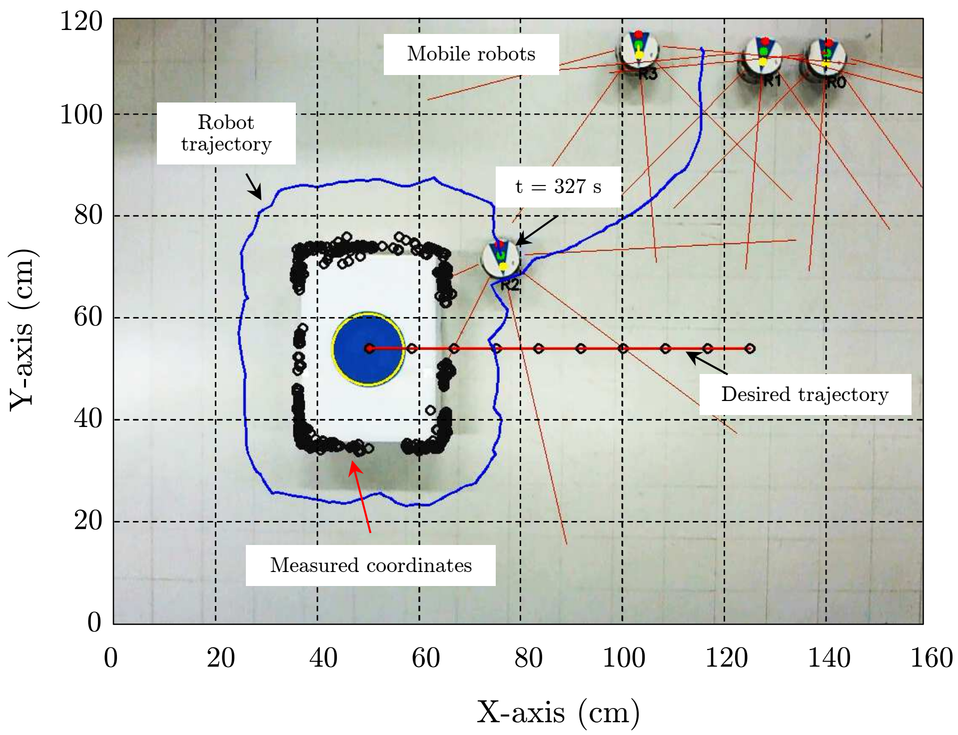


Figure 5.6: Object coordinates measure and record

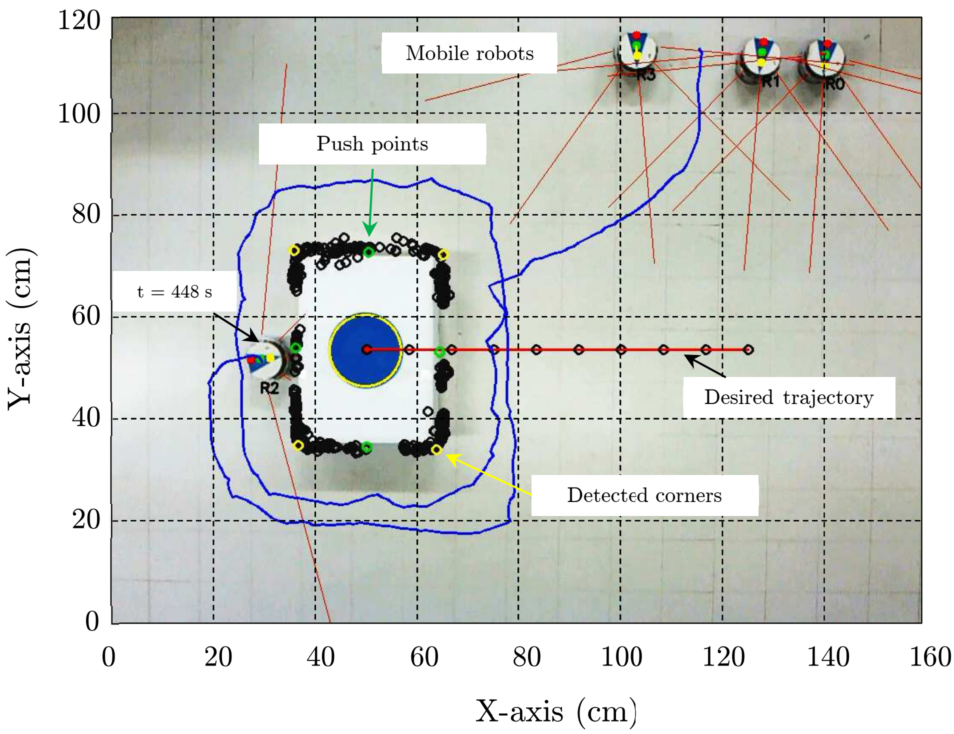


Figure 5.7: Push points estimation

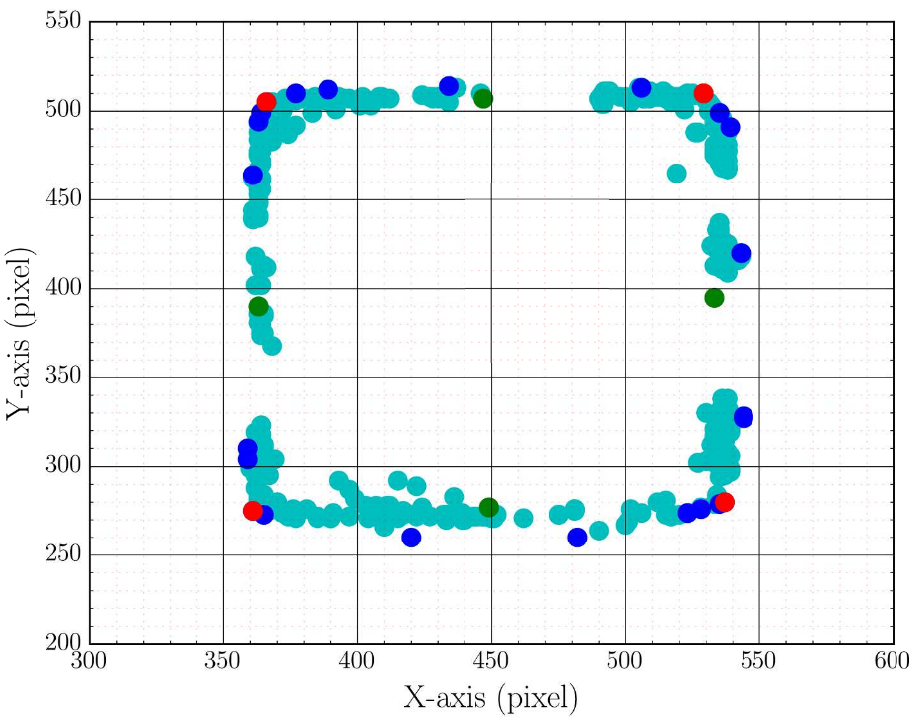


Figure 5.8: Generating convex hull and corners detection

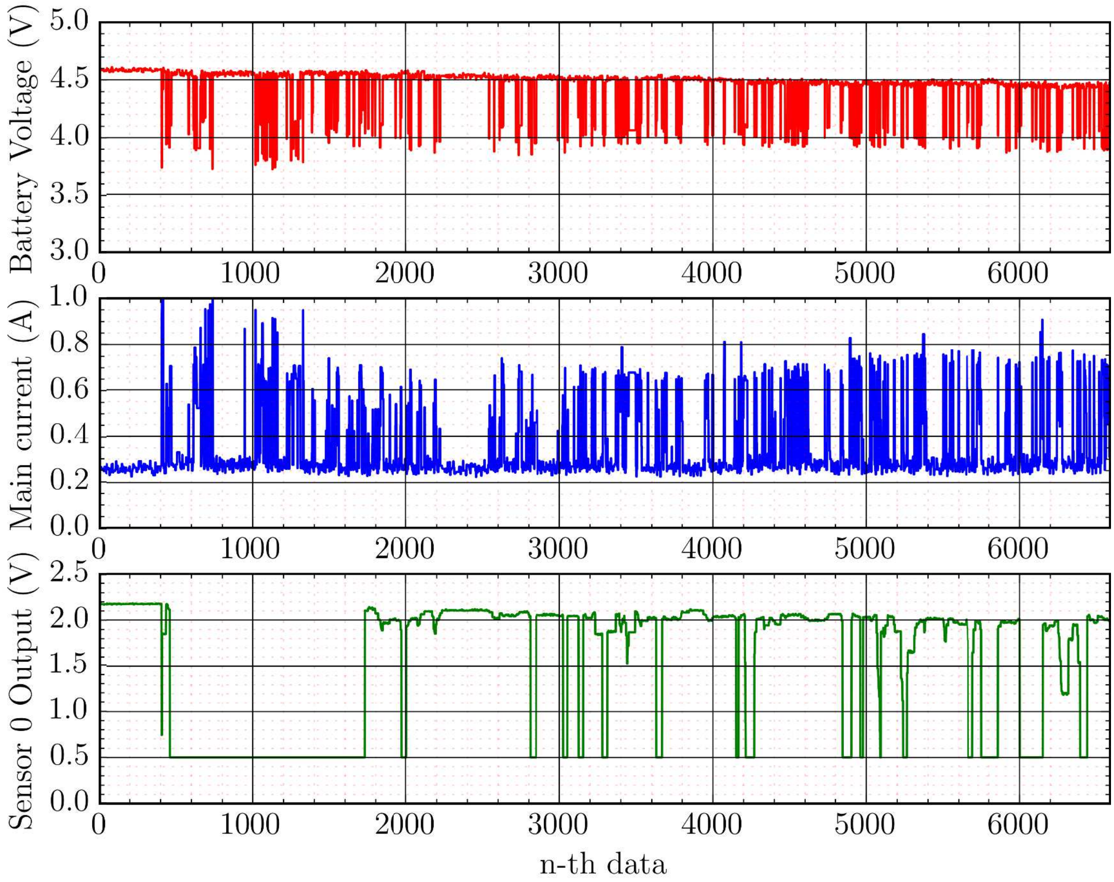


Figure 5.9: Surveyor robot voltage, current and sensor data

Since the mobile robot is equipped with the voltage, current and distance sensors, these data are able to be retrieved during operation. Fig 5.9 shows the voltage, current and sensor 0 values from the beginning of surveyor robot approach until arrive at push point. There are 6519 data that are recorder in 447 seconds. The voltage graph (red color) shows that the changing of battery voltage from 4.6V to 4.48V during the operation. It is caused by motor movement that consumes high current. The current data shows that the motors movement drains the battery current up to 1A at the beginning of process. However, it gradually decreases to 0.6-0.8A. The distance sensor data of surveyor robot is shown in Fig.5.9 with green color. It is noisy and unstable. Therefore, the limiter is applied to the distance sensor data value. The distance sensor is made only able to work between 5cm to 20cm from the original function of 50cm reading.

5.3 Results of object conveyance

The second experiment is the object conveyance where includes overall process from the surveyor robot approach until object conveyance to final sub-goal as shown in Figs. 5.10-5.18. The object push point estimation results are shown in Figs. 5.10-5.12. This process is similar to the results at previous experiment. In this experiment, the surveyor robot arrives at near of the object in 65s then it surrounds to measures the object coordinates. The push point estimation works properly for different coordinates and results correct push points even though there some noisy coordinates at corners.

In the Figures, the distance sensor readings are shown by five red lines for each robot with 50cm maximum reading. This indicator may show incorrect value if the developed computer program cannot receive data packet sent by each mobile robot. In Fig. 5.10, the surveyor robot (R2) sensor indicator works properly as actual sensor reading. However, the R1 sensor indicator does not work properly because of the communication error. Therefore, R1 is selected as standby robot that does not join the object conveyance process.

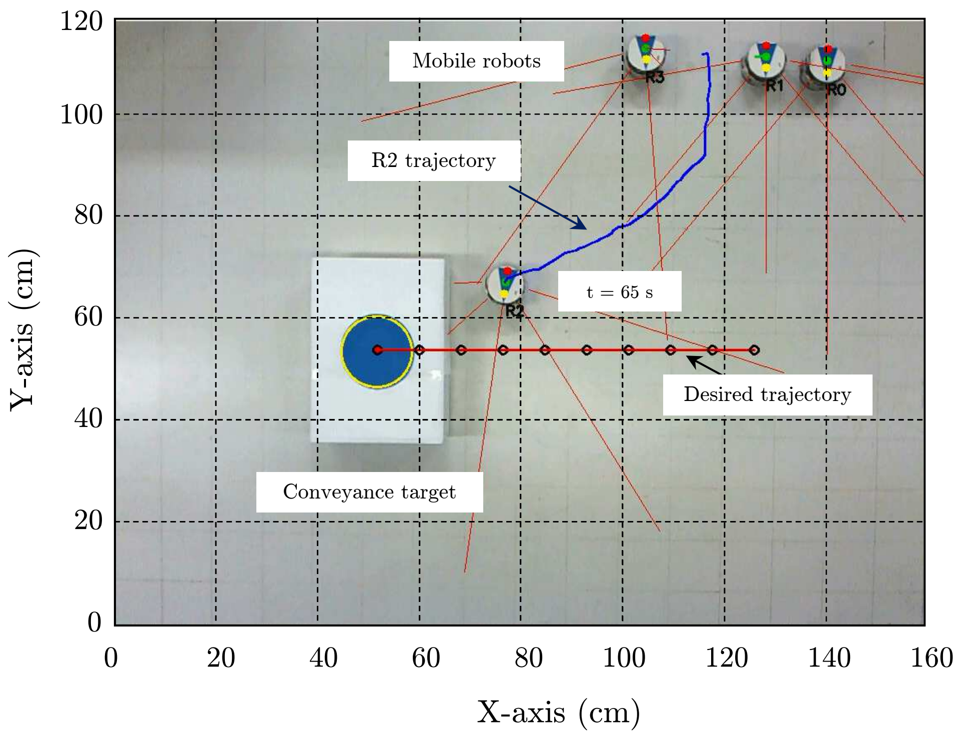


Figure 5.10: Surveyor robot (R2) approaches the object

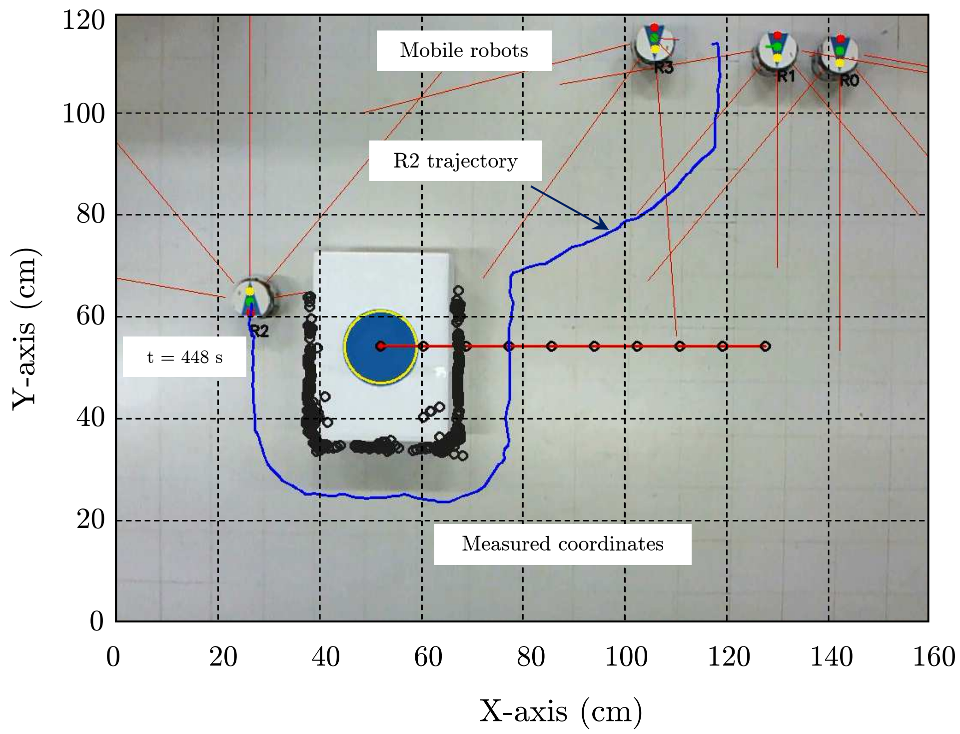


Figure 5.11: Surrounds and measures object coordinates

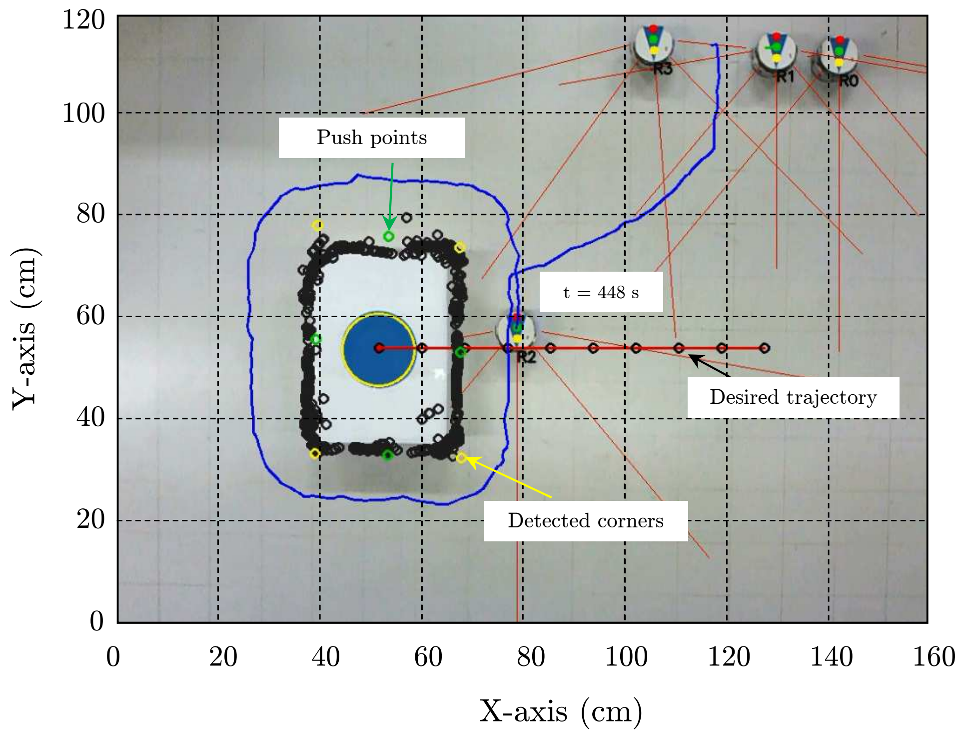


Figure 5.12: Push point estimation result

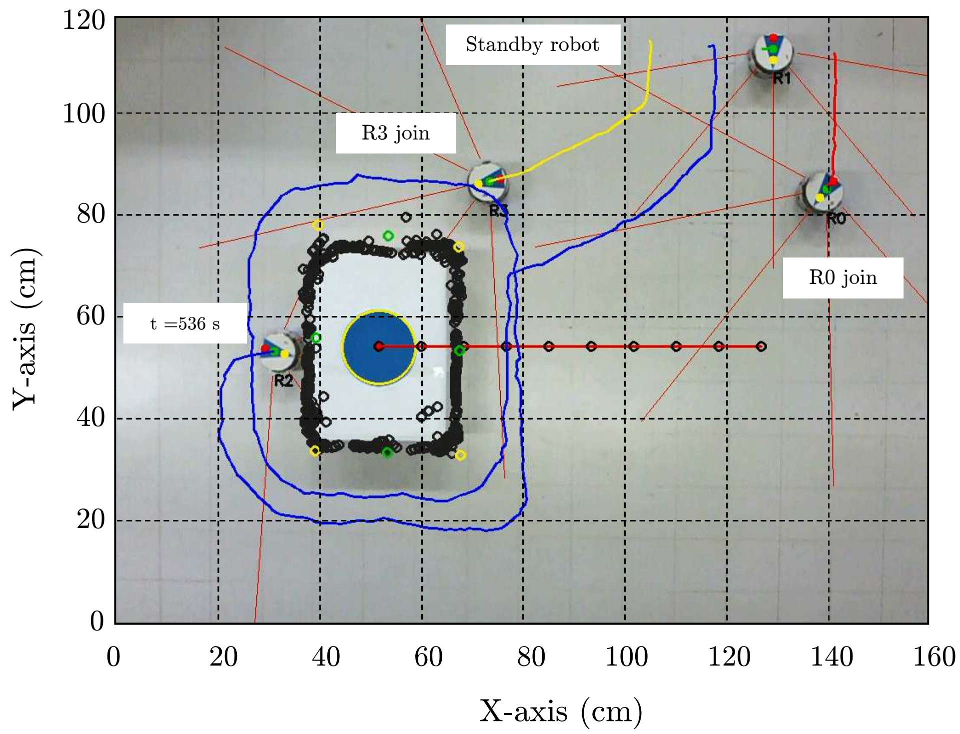


Figure 5.13: Surveyor robot (R2) arrives at its push point while R2 and R3 join

The object conveyance processes are shown in Figs. 5.13-5.18. In the Fig. 5.13, surveyor robot arrived at its push point in 536 seconds from the beginning. The robot R3 and R0 approach their push points that are estimated in previous processes. The result shows that the distance of R3 to its push point is closer that R0 to its push point. It takes 1070 seconds for all robots arrived at their push points as shown in Fig. 5.14. From here, the robots are ready to push the object.

As the previous explanation, the robot coordination is performed by using two methods, virtual structure and slide mode control. The virtual structure is created after the surveyor robot surrounds the object and estimates the object shape. It use basic triangular structure which consist of one pusher robot located at behind of the object and two aligner robots located at the both sides of the object. The sliding mode control enables each robot to move on their correct trajectory in order to deliver the object on the desired trajectory. Because of the different condition of each robot, it may lag or lead for making the triangular virtual structure. However, Figs. 5.15-5.18 show that the object trajectory is similar to the desired trajectory and it indicated the correctness of the proposed approaches.

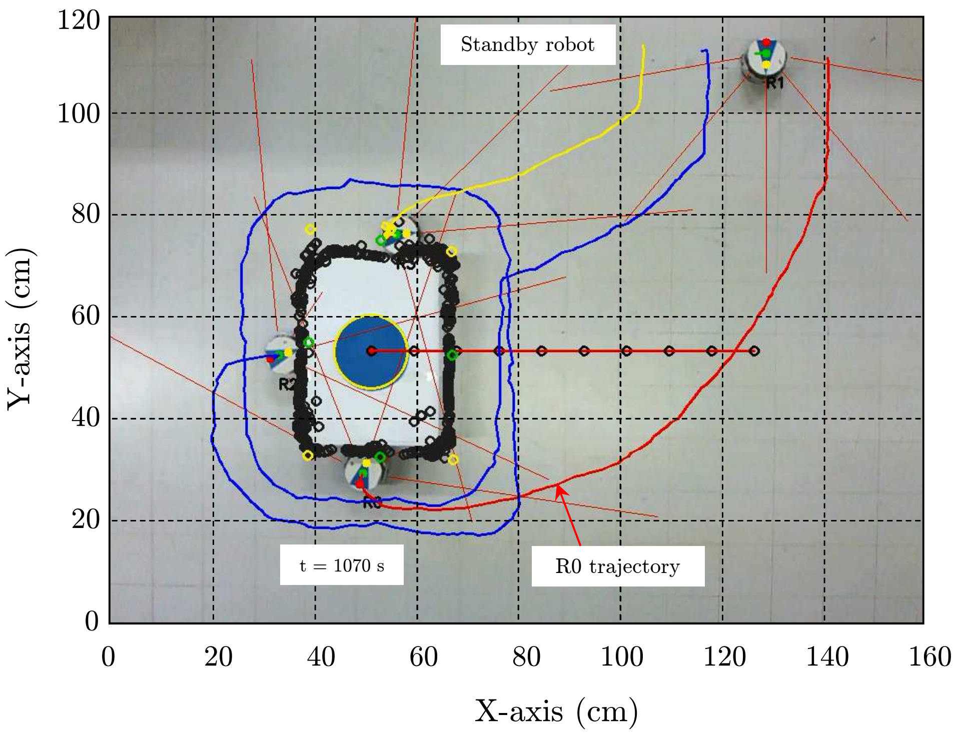


Figure 5.14: All robot arrive at their push points

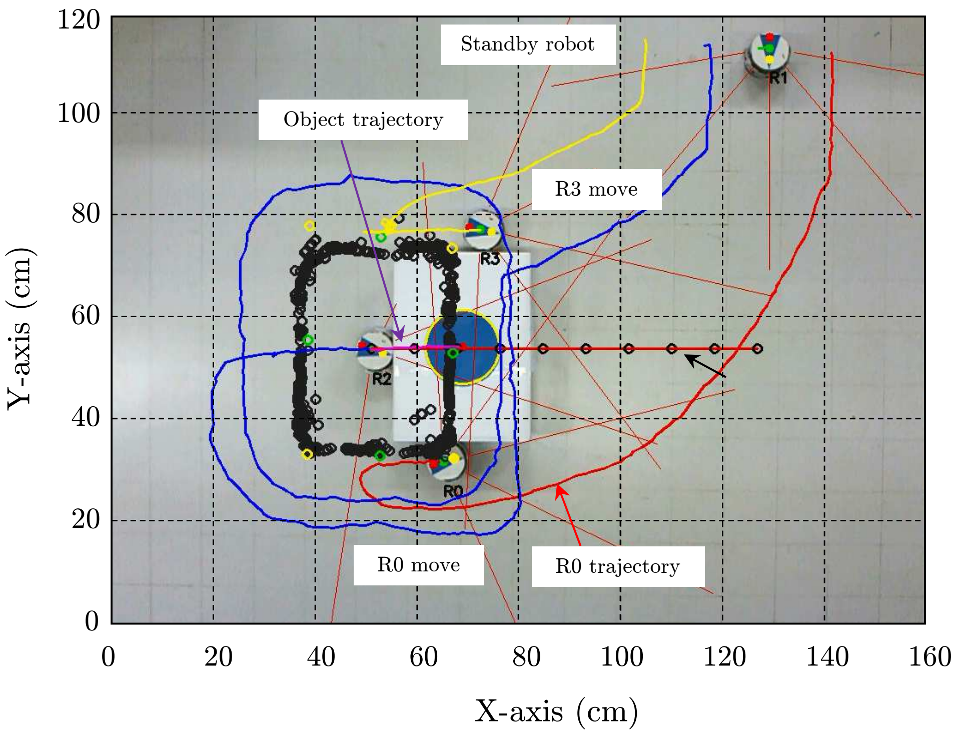


Figure 5.15: Object conveyance at 3rd sub-goal

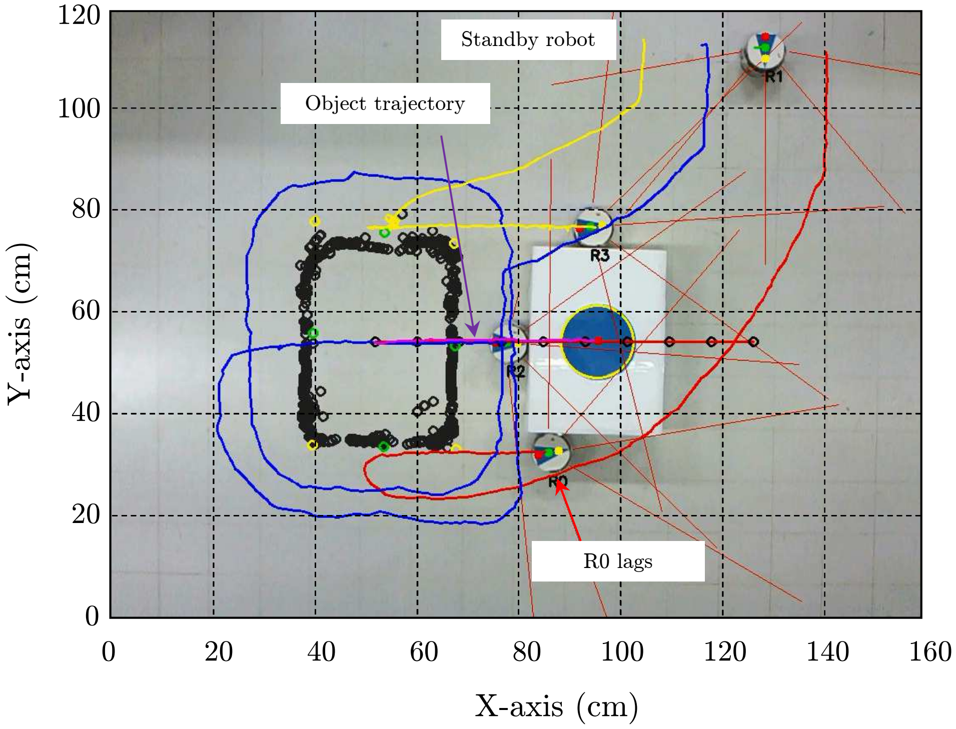


Figure 5.16: Object conveyance between 6th and 7th sub-goal

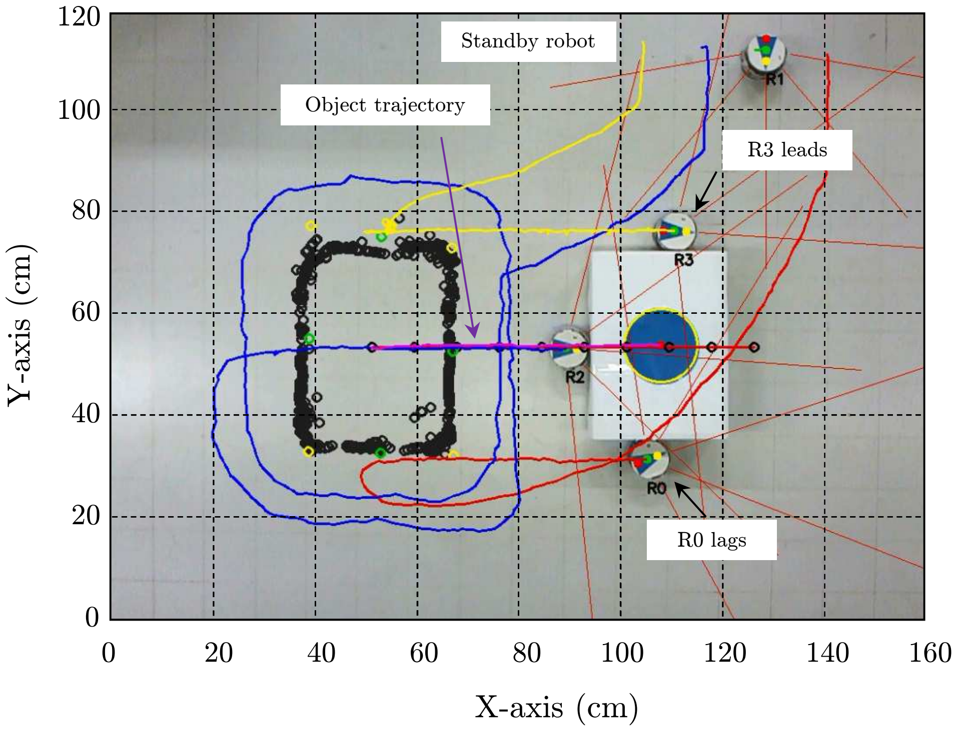


Figure 5.17: Approaching 8th sub-goal

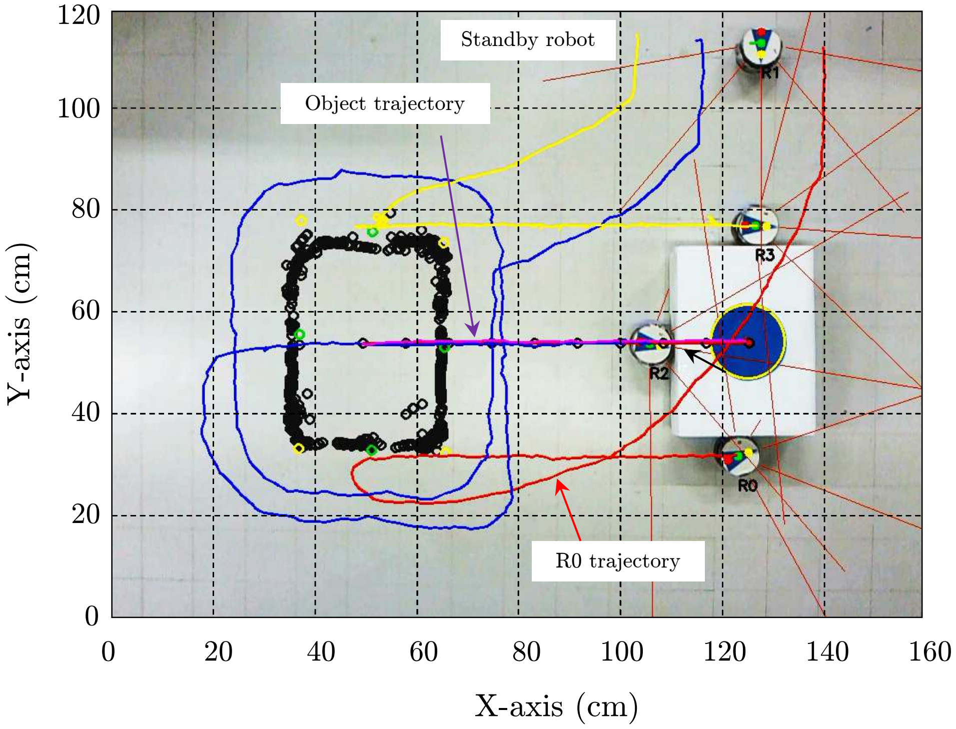


Figure 5.18: Arrive at final sub-goal

CHAPTER 6

Conclusion

The algorithm for determining the number of the robot in multiple mobile robot object conveyance is developed and verified in a simulation with regular shape and irregular object. It demonstrates the effectiveness in searching push points both regular and irregular object. The obtained push point is used by surveyor robot to make initial push of object conveyance. Also, the object conveyance by three robots is also verified in simulation with two different trajectories and object weight. The proposed method that uses simple robot configuration can adapt the number of robot in object conveyance based on object shape, shape and weight.

The first simulation result uses three robots that are divided into one pusher robot and two aligner robots. Pusher robot is required to push from behind the object and the aligner robots are required to navigate object conveyance so the object can be transported on the desired trajectory. The aligner robots are added because it is realized that the conveyance by single robot cannot maintenance object orientation. In addition, as the heavy object needs more push power, additional robots will join for moving the object along trajectory. In this research, it is examined up to five robots in three combinational straight lines trajectory. Moreover, the use of virtual structure and sliding mode control for moving algorithm of the multiple mobile robots are demonstrated.

It is convinced that there are a lot of the potential applications of proposed method such as indoor cleaning robot system and automatic warehouse system. In the future, proposed algorithm will be verified in an experimental as a method for defining push point in object conveyance by multiple mobile robots. Also, while the system has been discussed, it should be noted that the real system of future work will be designed to increase applicability.

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APPENDIX A

Hardware

A.1 ARM Cortex-M4 microcontroller

The STM32F407VGT7 with ARM Cortex®-M4 processor as shown in Fig. A.1 is used in this research. This microcontroller is one of the most advanced microcontrollers since it reached the industry's highest benchmark scores for Cortex-M-Based microcontrollers. With 168MHz clock speed and 1024kb program memory, it can handle a multitasking process such as moving two servo motor, wireless communication, reading analog sensors, and battery power monitoring. Detail specification is shown in table A.1.

(a) Top-view (b) Bottom-view

Figure A.1: Cortex®-M4 STM32F407

Table A.1: Specification of Cortex®-M4 STM32F407

Parameter	Description	Unit
Architecture	ARM Cortex-M4	-
CPU Speed	168	MHz
Program Memory Size	1024	KB
RAM Memory Size	196	KB
No. of Pins	100	Pins
Package	LQFP	-
No. of I/O	82	I/O
No. of Timers	17	-
Interface	CAN, ENET, I2C, SPI, UART, USART, USB	-

A.2 Wireless communication module

A wireless communication unit used in the robot of this research is XBEE RF module. The manufacturer is MAXSTREAM, Inc. which was acquired by Digi International in 2006. XBEE with IEEE 802.15.4 standards offers a low-cost and low-power wireless data exchange. It is suitable for use in multiple mobile robot systems. Figure A.2 shows the physical appearance of the XBEE. The specification is shown in Table A.2.

Figure A.2: XBEE RF module

Table A.2: Specification of XBEE RF module

Parameter	Description	Unit
Protocol	ZigBee	
RF data rate	250000	bps
Transmit power	1	mW
Operating frequency	2.4	GHz
Indoor range	30	m
Outdoor range	100	m
Supply voltage	2.8-3.4	V

A.3 Servo DC Motor

A small movement actuator is needed to realize 7cm circular two-wheeled mobile robot. The chosen GWS PICO STD servo is the smallest of Grand Wing Servo-Tech Co., LTD product. It is a perfect tiny actuator for our small robot mechanism. Like other radio control servos, the GWS PICO LTD has three wires for ground, power, and control signal. The control signal is a PWM (pulse width modulation) signal with 20ms period. To drive the servo motor, the control signal is set from 1ms to 2ms. It will rotate this servo within 180-degree sweep at standard. Therefore, the servo requires a modification in order to enable it to spin full rotation. this servo is modified by changing internal mechanism. Detail specification of GWS PICO STD servo is shown in Table A.3.

Figure A.3: GWS PICO STD servo

Table A.3: Specification of GWS PICO STD servo

Parameter	Description	Unit
Torque	0.7	kg @4.8V
Weight	5.4	gram
Speed	0.12	per 60 degree @4.8V
Length	22.8	mm
Width	9.5	mm
Height	16.5	mm

A.4 Distance sensor

The distance sensor is used to add environment sensing capability to our small robot. The suitable sensor is GP2Y0E02A which is one of the IR-LED based distance sensor line-up from SHARP. The output of GP2Y0E02A is an analog voltage thus easy to combine with any controller for useful application such as robot, touch switch, and proximity sensing device. The physical appearance of GP2Y0E02A is shown in Fig. A.4 and its specifications are shown in Table A.4.

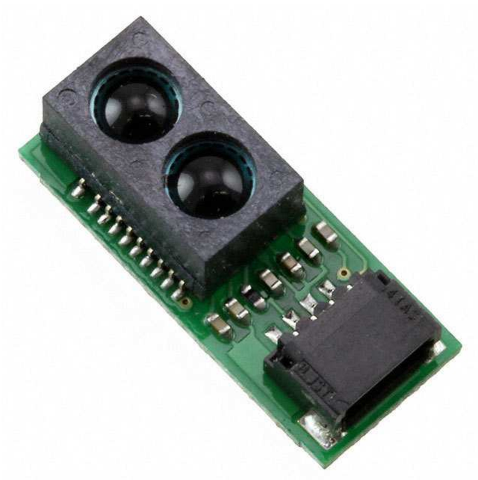

Figure A.4: GP2Y0E02A

Table A.4: Specification of GP2Y0E02A

Parameter	Description	Unit
Measuring distance	4-50	cm
Analog output	2.2 to 0.58	V
Supply voltage	-0.3 to +3.6	V
Length	18.9	mm
Width	8.0	mm
Height	5.2	mm

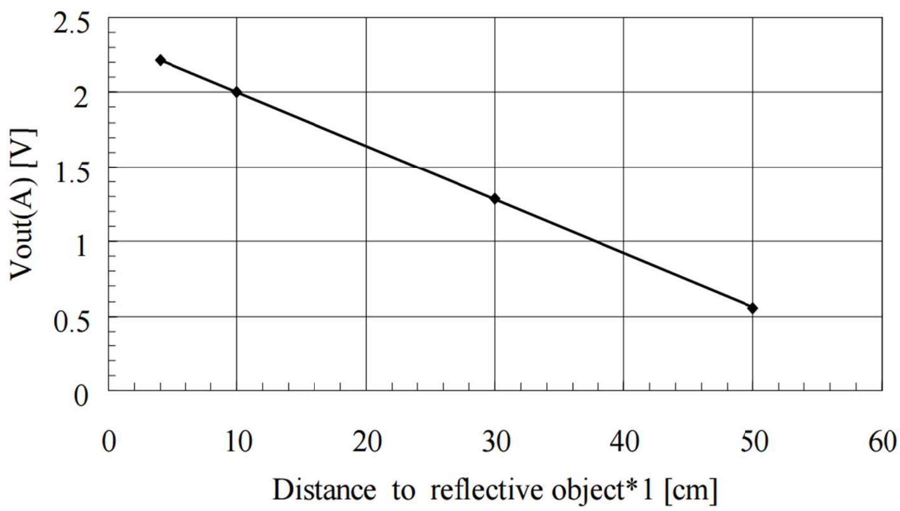

Figure A.5: Output distance characteristics of GP2Y0E02A

◇ ◇ ◇ Publications ◇ ◇ ◇

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2. P. Sejati and T. Yasuno, ”Push Position Estimation for Irregular Object in Conveyance Problem Using Multiple Mobile Robots System” in *International Design and Concurrent Engineering Conference*, Tokushima, September, 2015.
3. P. Sejati, H. Suzuki, T. Kitajima, A. Kuwahara and T. Yasuno, ”Object Conveyance Algorithm for Multiple Mobile Robots based on Object Shape and Size,” *International Journal of Advanced Computer Science and Applications,* vol. 7, no. 5, pp. 553-559, 2016.
4. P. Sejati, H. Suzuki and T. Yasuno, ”Investigation of Collision Signal Measured with Accelerometer for Determining Team Member on Non-Prehensile Object Conveyance by Multiple Mobile Robots” in *SICE Annual Conference*, Tsukuba, September, 2016.
5. M. Higashi, H. Suzuki, P. Sejati, T. Kitajima, T. Yasuno and A. Kuwahara, ”Investigation of Teleoperation Support System Using Environmental Recognition Sensors for Three-Parrarel-Crawler-Type Mobile Robot” *Journal of Signal Processing*, vol. 20, no. 5, pp.187-190, 2016.
6. M. Higashi, H. Suzuki, P. Sejati, T. Kitajima, T. Yasuno and A. Kuwahara, ”Investigation of Teleoperation Support System Using Environmental Recognition Sensors for Three-Parrarel-Crawler-Type Mobile Robot” in *International Workshop on Nonlinear Circuits, Communications and Signal Processing (NCSP’16)*, Honolulu, 2016.

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