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# An Infrared Docking System for Modular Wheeled Mobile Robots

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**Abstract**

A modular wheeled mobile robot is composed of autonomous wheeled modules capable of self-assembling to form up a modular mobile robot. The robot can change the number of its modules by having the modules detach themselves from the main body and move independently. In this paper, we propose a docking system for such robots, including a connection mechanism and a docking guidance system. The connection mechanism includes reconnectable opponents which allow the modules to connect to and disconnect from one another. The infrared docking guidance system is used to steer the modules and keep them aligned until they are docked.

**Key words:** Docking guidance, Connection mechanism, Wheeled mobile robots.

## 1. Introduction

Modular robotic systems, inherently robust and flexible, continue to challenge researchers (Gross et al., 2006). Robots that can change shape are built for chain, lattice, or mobile reconfiguration. Mobile self-reconfigurable robots change shape by having modules detach themselves from the main body and move independently. They then link up at new locations to form new configurations. This type of reconfiguration is less explored than the other two because the difficulty of reconfiguration tends to outweigh the gain in functionality (Yim et al., 2002).

Creating self-reconfigurable robot systems poses many engineering challenges centered on designing the basic self-reconfiguring module and inter-module connections, as well as on how to aggregate the modules into a single structure. The modules should be as small and simple as possible in terms of physical size, linkages, and functions. Simplicity is also a key consideration in designing the guidance system, and the connection mechanism. The connections should be simple and reliable since the modules may assemble and reassemble frequently.

We have already presented the design details of the connection mechanism in our previous work (Delrobaei and McIsaac, 2009). The proposed mechanism is suitable for our application since it is lightweight, compact, and powerful enough to secure a reliable connection. It overcomes significant alignment errors, and it is considerably power efficient. So, here we focus more on the docking guidance system.

## 2. Related Work

A docking guidance system is needed to steer the modules and keep them aligned until they are docked. Infrared emitter/receivers are widely used for guiding two robot modules to align (Gross, 2006), (Rubenstein et al., 2004), (Khoshnevis et al., 2001). In most works, the alignment quality is estimated by measuring the strength of infrared signals. Roufas et al. (2001) presented an easy and inexpensive implementation of a six DOF offset sensing mechanism for automatic docking mechanisms.

Kemppainen et al. (2006) presented an infrared location system for relative position and orientation estimation in a multi-robot system where each member of the group locates and recognizes other robots. The implemented system consists of an IR emitter and a rotating beam collector.

A few researchers have reported localization using sonar systems. Shoval and Borenstein (2001) presented a method for measuring the relative position and orientation between two mobile robots using a dual binaural ultrasonic sensor system. Each robot is equipped with a sonar transmitter that sends signals to two receivers mounted on the other robot.

In some works, laser range finders have been used to implement relative position estimation systems. Schneider and Wildemuth (2004) presented a new approach to relative position estimation in multi robot systems. In this work, the information of a laser scanner is used to estimate the relative positions between the robots. Montesano et al. (2004) used two mobile robots both equipped with two laser range scanners which together provide a 360 degrees field of view.

Visual navigation is increasingly becoming a more attractive method for robot navigation (DeSouza and Kak, 2002). Montesano et al. (2005) have presented a method to relatively localize pairs of robots fusing bearing measurements and the motion of the vehicles. Bearings are obtained as direct readouts of the omnidirectional cameras.

Mondana et al. (2004) presented the Swarm-bot platform. For the purpose of communication, the s-bot is equipped with eight RGB LEDs distributed around the module, and a video graphics array (VGA) omnidirectional camera. The camera can detect s-bots that have activated their LEDs in different colors.

Docking systems which use cameras to detect the other modules are generally complex (DeSouza and Kak, 2002), (Montesano et al., 2005). So, as it is intended to have simple and small-sized rovers, using camera seems improper. Laser sensors are generally large, and cannot distinguish the objects (Schneider and Wildemuth, 2004). So, we ignore using laser range finders. A docking system based on sonar sensing appears not to be effective for our work, since reflection from other objects makes the system unreliable.

Therefore, using infrared (IR) seems to be the most appropriate option. IR is simple to work with, and IR sensors/emitters are small-sized, light-weight, and power-efficient. However, except for one proposed system (Kemppainen et al., 2006), all the other IR docking systems are based on measuring the angle/distance between a set of fixed IR emitters/receivers (Rubenstein et al., 2004), (Khoshnevis et al., 2001), (Roufas et al., 2001). This configuration does not allow to have a wide-ranging docking system (for PolyBot (Yim et al., 2002) and CONRO (Shen, and Will, 2001) the docking range is limited by 15 cm and ±45◦).

Kemppainen et al. (2006) have shown that it is possible to have a wide-range detection (up to 3 m) using an IR beacon, and a rotating beam collector. However, the proposed approach suffers from a major drawback. This system can only detect the position and it is unable to detect the orientation of the target robot in 2-D space. So, this system appears to be ineffective for our application.

Therefore, part of this work includes investigating the possibility of having an exact yet wide-ranging IR docking system which is capable of detecting the position and orientation of the target robot.

## 3. Connection Mechanism

As mentioned, the design details of the proposed connection mechanism is fully discussed in our previous work (Delrobaei and McIsaac, 2009). Here we only present the final design of the mechanism.
This mechanism consists of a male piece and a female opponent which join together, and a locking mechanism that locks the joint. The spherical head of the male piece and the excavated groove provide a smooth docking, and allow significant misalignment. The slots on both male and female connectors let a key lock the joint. This mechanism is advantageous in that it is compact and easy to use, which makes it reliable. Moreover, the mechanism is quite power efficient, because activation of the actuators is needed only during the opening and closing phase. Fig. 1 shows the physical implementation of the proposed connection mechanism.

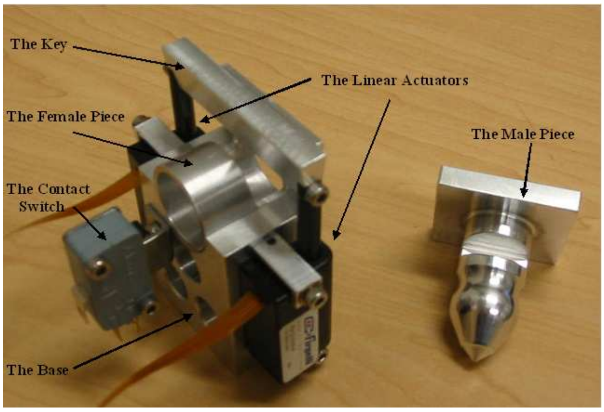


Fig. 1. The physical implementation of the docking mechanism.

## 4. Docking Guidance System

In order to complete the docking maneuver, the rover should control its heading direction and follow a smooth path towards the target rover. Therefore, an exact yet wide-ranging relative pose system for detection and localization of the target is needed. Due to the small size of the rovers, this system should be lightweight and small, while still provides sufficient system accuracy.
This section presents the design details of the infrared docking guidance system.

### 4.1. Configuration

The first question and the one following that are: how many pairs of IR emitters/receivers are needed, and how they should be placed on the rovers.
To answer the first question, we consider three cases. In case one, there is one omnidirectional IR emitter on the target robot, and a rotating beam collector on the approaching rover. Using this configuration, the position of the target robot can be identified by measuring the IR signal strength, but there is no way to detect its orientation (Kemppainen et al., 2006). So, this configuration is not acceptable.
In case two, there is one directional IR emitter on the target robot, and a fixed IR receiver on the approaching rover. In this method, the distance and angle between the rovers can be estimated using the IR signal strength. This configuration can be extended to use more pairs of fixed IR emitters/receivers (Roufas et al., 2001), but this method is normally used

for very short distances and cannot be wide-ranging. Therefore, this configuration does not meet requirements.

The third case is to use three omnidirectional IR emitters, placed on a triangle, and a rotating beam collector. This approach has not been addressed in the literature before, and seems to be the best choice, since it can identify the position and orientation of the target only based on measuring the angles between the beacons. Therefore, measuring the signal strength is not needed (i.e. it is only based on detecting the beacons), and the system can be designed such that it is wide-ranging.

Figure 4 shows the basic idea of this method. According to this figure, three beacons are located on the vertices of a triangle (A, B, C), and the beam collector is considered to be located in three different positions (a, b, c). When the beam collector is on the right track (Fig. 4 (b)), the beacons are seen in order (ABC; considering the beam collector to be rotating clockwise), and the measured angles (AB, BC) are the same.

If the beam collector is approaching the beacons from the left corner (Fig. 4 (a)), the beacons are seen in a different order (BAC; considering the beam collector to be rotating clockwise), and the measured angles (BA, AC) are not necessarily equal. If the beam collector is approaching the beacons from the right corner (Fig. 4 (c)), the beacons are seen in another order (ACB; considering the beam collector to be rotating clockwise). Considering the geometry of the system, the rover should be moving exactly on the desired track to see the beacons in ABC order, with the same angles.

So, every time the beam collector rotates, the control system gets an update of the order and the angle of the beacons, and tries to make angle AB equal to angle BC. In fact, the beam collector provides feedback to steer the rover towards the target.

### 4.2. IR Beacons

Each rover has three IR beacons for the purpose of signaling other rovers, and each beacon has a unique modulation frequency from which it is recognized. The beacons are mounted on the top part of the rover, on the corners of a triangle, and at different levels. The beacons are turned on in the beginning of the docking maneuver.

As the system is supposed to be working in untraditional environments, the rovers may be required to operate very close or far from each other. To maximize the measurement range, infrared radiation is reflected sideways into a uniform zone using a conical mirror. Figure 5 shows how the beacons will be mounted on each rover.

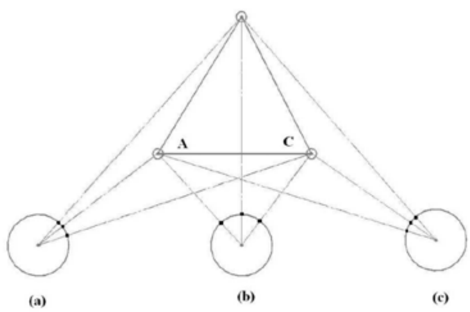


Fig. 4. The basic idea of the guidance system. Three beacons are located on the vertices of a triangle; (a) If the beam collector is approaching the beacons from the left corner, the beacons are seen in BAC order (the beam collector is rotating clockwise), and the measured angles are not equal; (b) When the beam collector is on the right track the beacons are seen in ABC order and the measured angles are the same; (c) If the beam collector is approaching the beacons from the right corner, the beacons are seen in ACB order and the measured angles are not equal.

### 4.3. IR Beam Collector

The first job for the robot is to locate the goal robot's beacons. The location system performs direction estimation by rotating a beam collector at a constant rotation speed. The beam collector detects the beacons and measures the angles between them. IR signals are received through small apertures in the beam collector, enabling accurate bearing measurement (Fig. 5).

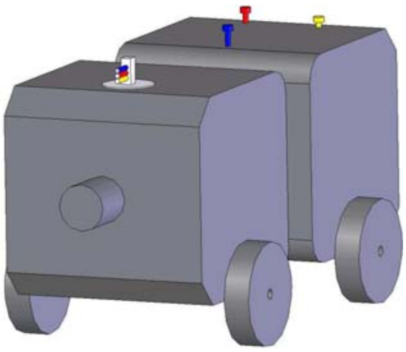

Fig. 5. The position of the beacons, and the beam collector.

The beam collector will have three IR detectors shrouded by small tubes. So, the sensors will not be bombarded at multiple angles. Each detector will receive signals from its counterpart once it is within the signal range and scope. These shrouded sensors then will mount on top of each other and all will be mounted on a tiny servomotor. The rotation of the sensors can be recorded to provide the angle where the beacons are located relative to the robot. The servo rotates at a full $180^{\circ}$ and then returns $180^{\circ}$ back. The control system will use this information to adjust the steering angle so that the approaching rover will face the target rover.

### 4.4. Control System

The docking control system is first required to identify the target rover beacons, and then the angle between them is determined. As the approaching rover moves toward the target rover, its steering angle will be continuously updated based on the feedback from the beam collector.

The pose (position and orientation) of a planar mobile robot is defined by its lateral (X, Y ) and angular (θ) position (Fig. 6). Assuming the center of the beam collector to be the origin of the main coordinate system, it is observed from Figure 7 that once the detected angles (α and β) are equal and the beacons are seen in order, both rovers are aligned.

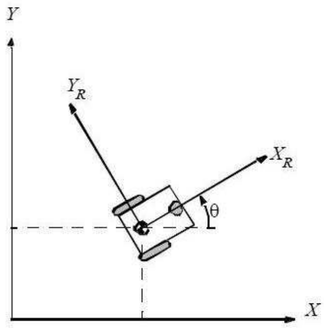


Fig. 6. The position and orientation of a planar mobile robot; defined by (X, Y,θ).

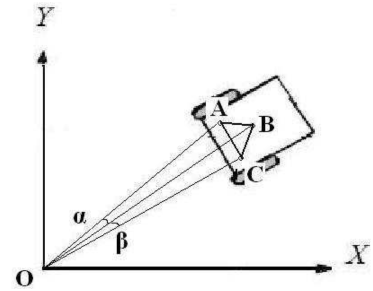


Fig. 7. The rovers are aligned once the detected angles are equal and the beacons are seen in order.

Therefore, the control system tries to make α equal to β, using a simple PID controller (Fig. 8).

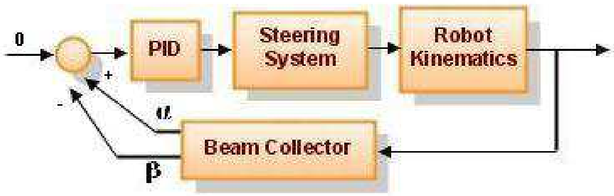


Fig. 8. The control system tries to make α equal to β

It is straightforward to show that making α equal to β is sufficient to align the robots. Considering Fig. 7, and defining $OA = l_1, OB = L, OC = l_2$, and $AB = BC = l$; for the triangles $\Delta OAB$ and $\Delta OBC$ we can write

$$l^2 = l_1^2 + L^2 - 2l_1L\,cos\alpha \qquad (1)$$

$$l^2 = l_2^2 + L^2 - 2l_2L\cos\beta \qquad (2)$$

If $\alpha = \beta$, (1) and (2) can be simplified as

$$(l_1 - l_2)(l^2 - L^2 - l_1l_2) = 0 \qquad (3)$$

As $l << L$, (3) implies that $l_1 = l_2$. Therefore, making $\alpha$ equal to $\beta$ is sufficient to drive the approaching robot on the right track, where $l_1 = l_2$.

## 5. Experimental Results

In this section, experimental studies are carried out to evaluate the performance of the docking system. The experiments are designed to investigate the capabilities of the docking system, and to measure the range of the guidance system. The followings discuss the experimental setup and results.

### 5.1. Experimental Setup

Fig. 9 shows the experimental setup, utilized to evaluate the performance of the proposed docking system. The setup includes two mobile robots. The connection mechanism base is fixed on the back of the goal robot, and the pin is located in front of the approaching robot.

The goal robot is stationary, and the moving robot is free to approach from different directions. It is noted that these robots are used only to identify the system's capabilities,

and they are not those that will be utilized in the final system.
The goal rover has three IR beacons for the purpose of signaling the other rovers. Every beacon has a unique modulation frequency from which it is recognized. These beacons will run at 30 kHz, 38 kHz, and 57 kHz. The beacons are mounted on top of the rover, on the corners of a triangle, and at different levels. The beacons will be turned on in the beginning of the docking maneuver.
A beam collector is fixed on top of the approaching robot which utilizes three IR photo ICs sensitive to 950 nm infrared wavelength with 30 kHz, 38 kHz, and 57 kHz carrier frequencies. The detectors are mounted on top of a tiny servomotor.

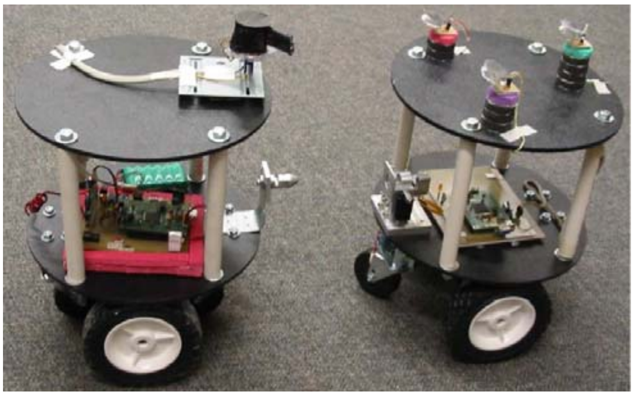

Fig. 9. The experimental setup; the approaching rover (left), and the goal rover (right).

### 5.2. Results

Our primary concern was to determine the docking range. The docking range can be defined as the initial configuration from which the approaching robot could successfully dock with the target rover.
According to Figure 10, the center of the goal robot is stationary at point (0,0) (so, the docking mate is located at point (17,0)), and the other robot is free to approach from different directions. Enough trials were performed to determine the docking range. Figure 10 shows a cone shape pattern. If the approaching robot is positioned within this cone shape region, it can successfully dock with the goal robot.
Figure 10 does not show the initial orientation of the approaching robot. As far as the initial orientation of the approaching rover allows the beam collector to detect all three beacons, the robot finds the goal while it is within the range.

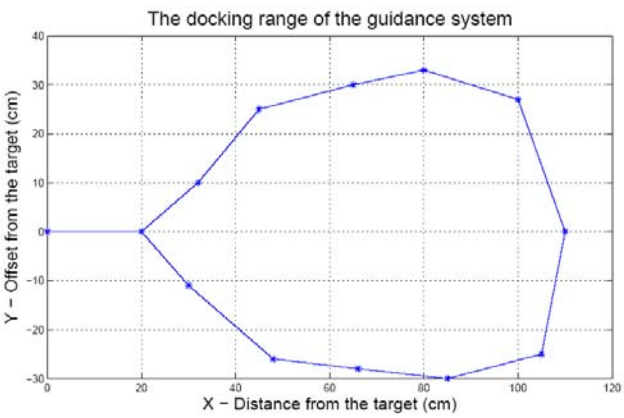


Fig. 10. The docking range of the proposed guidance system. Note that the docking mate is located at point (17,0).

## 6. Conclusion

In this paper, a docking strategy to align and connect mobile modules has been presented. The complete control system was successfully developed, implemented and tested on differential-drive mobile robots.

It is observed through the experiments that the proposed docking guidance system has a distinctive feature in that the rovers make use of local sensing abilities which makes the system simple and reliable. In fact, there is no need to measure IR signal strength, since it is only based on detecting IR beacons.

Most of the docking systems presented so far seem to be too complex for a simple docking task. The guidance system discussed in this paper does not need complex sensors and algorithms. Therefore, it is suitable for small mobile robots.

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