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Rendezvous of Heterogeneous Robots Amidst Obstacles with Limited Communication

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Abstract— **We consider the problem of *rendezvous* between a pair of mobile robots. The robots could be heterogeneous. We assume communication is limited to infrared beacons on each robot. No *a priori* knowledge of the positions of the robots is required. We present an algorithm for rendezvous of the robots in an environment that may contain one or more obstacles. We also address the issue of *ambience* when dealing with infrared beacons. Experiments with a mobile robot and a bipedal robot are presented to validate the efficacy of the proposed algorithm.**

Index Terms— **Rendezvous, infrared (IR) beacons, algorithm, bipedal robot, mobile robot**

I. Introduction

Teams of robots are typically employed for various purposes. A team may complete a task faster than a single robot. On the other hand, a team may also be necessary to accomplish certain tasks. Robots that need to interact to accomplish some task may not be physically at the same location. They may be distributed and need to come together. This is commonly referred to as the *rendezvous* problem in the literature. The rendezvous problem has been studied by researchers in computer science, economics, control and other domains with different assumptions and objectives. An early paper on rendezvous is due to Alpern [1] in the context of hide and seek games. The last two decades have seen enormous activity on various versions of the rendezvous problem. Extensions and variations of the work in [1] have been presented in [2], [4] and [3]. There have also been efforts on rendezvous by agents/autonomous robots from a control point of view [5], [11]. Coordination algorithms for mobile robots with visibility sensors have been reported in [7]. A leader-following rendezvous problem for a double integrator multi-agent system has been studied in [6]. Extensions of rendezvous algorithms for the plane to 3-D have also been explored [10]. Rendezvous of multiple non-holonomic unicycle-type of robots has been studied in [12].

In this paper, we consider the problem of *rendezvous* between a pair of mobile robots when the robots are equipped merely with infrared (IR) beacons. While rendezvous has been explored in general in the literature, work on rendezvous with specific constraints on the hardware carried is limited. Further, analysis of the capabilities of the hardware (for communication, sensing) to facilitate rendezvous in an environment with obstacles has been scarce. Our algorithm is applicable to heterogeneous robots as well and we report experiments on rendezvous with a pair of heterogeneous robots fabricated locally. An application of rendezvous is illustrated in Figure 1. The drum on the mobile robot in Figure 1 is assumed to have compartments (or openings) that allow transfer of material into/out of the drum. The drum can rotate (via a motor on the top surface of the mobile robot). As the drum rotates, a compartment is “lowered” so that the humanoid robot can reach the compartment and perform transfers. Our experiments involve a mobile robot and a bipedal robot.

There are several advantages of rendezvous using merely IR beacons. First, no knowledge of initial positions of the robots is required. Second, precise knowledge of the location of obstacles in the environment is also not required. We assume point-size (or small) robots and determine paths for the robots based on reflection of beams from the IR beacons. For larger-size robots, collision avoidance can be handled using additional sensors (for example, ultrasonic sensors). Further, with the IR beacon approach, one can devise an algorithm that obviates the need for additional hardware for communication (such as bluetooth) even if both the robots move to achieve rendezvous. To our knowledge, there has been no prior work on rendezvous with limited communication (such as using IR beacons) especially in the presence of obstacles.

A challenge posed by IR is the ambience. The beams tend to reflect from the surrounding walls and create an illusion of an additional robot in the vicinity. One solution to this problem is manipulation of the ambience by absorbing the waves instead of reflecting them. However, robots usually find their place in laboratories amongst other devices (and obstacles) so it is difficult to manipulate the ambience. The proposed approach addresses this challenge by adapting to the environment via calibration to the surroundings. In particular, the intensity of the lighting determines a threshold value to be set and this corresponds to determining if the signals from the IR beacons need amplification. Experiments on rendezvous of a biped and a mobile robot (fabricated in our laboratory) are presented to validate the proposed approach.

The remainder of this paper is organized as follows. In the next section, we present the assumptions and then develop the main results used for the description of the proposed rendezvous algorithm. Section III presents various subalgorithms for rendezvous, namely algorithms for adaptation and determination of direction for the robots. The section concludes with the proposed rendezvous algorithm. Section

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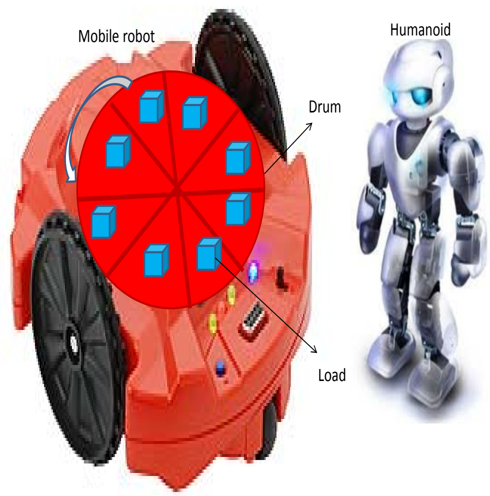


Fig. 1. Humanoid Robot working with a mobile robot; rendezvous required prior to the load/unload operation

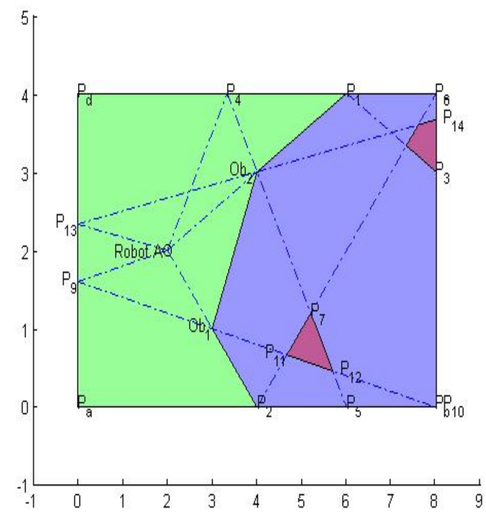


Fig. 2. Various zones for a transmitter placed at A in the presence of a line segment obstacle Ob_1Ob_2

IV presents the details of the experimental setup and results. Section V concludes the paper.

II. ASSUMPTIONS AND SOME KEY RESULTS

In this section, we state the assumptions for presenting our rendezvous algorithm. We also develop some results needed for the algorithm.

A. Assumptions

The assumptions used for development of the rendezvous algorithm are as follows.

1) The robots operate in an indoor environment.
2) There are six transmitters on each robot, each having a transmission angle of $60°$, thus covering the entire $360°$.
3) There exists at least one path between the two robots to rendezvous.

B. Terminology

While the transmitters cover $360°$, the entire area within the boundary does not necessarily receive the signal directly from the transmitter. Since we are working with IR beams, the signal may reflect off of many surfaces before it becomes incident on a given region. We represent regions based on the number of reflections a ray undergoes before reaching it.

The space in which the robots are operating in the presence of obstacles and polygonal walls is denoted by 'S'. The subset of 'S' over which the IR beam reaches without any reflection is termed as 'Zone 0'. The area over which the IR beam reaches after one reflection from any of the walls or obstacles is termed as 'Zone 1'. The receiver can detect an IR beam only above a certain intensity. Thus, the maximum number of zones will depend on the maximum number of reflections from various surfaces, walls and obstacles before the incident IR beam loses its minimum detectable intensity. This value of minimum detectable intensity will depend on the intensities of other light sources in the room along with the kind of reflective surfaces. This is termed as the Threshold value (T_v). The maximum value of zone numbers is defined as the 'Reflective index' and is denoted by R_n.

We denote the robots by A and B. Both the robots A and B have transmitters and receivers which can cover the entire $360°$ range. The transmitters on A and B are denoted by T_A and T_B respectively. The receivers on A and B are denoted by R_A and R_B respectively.

C. Some Results Pertaining to IR Transmission

Lemma 2.1: The change of zone happens due to the obstruction of IR beam by an obstacle.
Proof: In the absence of any obstacles, the IR beam with a $360°$ range of emission covers the entire room with its rays even before the rays hit any walls. When an obstacle is added, the area behind the obstacle as seen from robot A 'becomes dark' with respect to IR beam. However, the reflections from other walls are present and a part of this area lights up. This area is Zone 1. The border between Zone 0 and Zone 1 is thus due to the vertex/edge of the obstacle. Q.E.D

Remark 1: Fig. 2 gives an example of various zones in a rectangular room. The robot A (with its transmitters) is placed at (2,2) as indicated in the figure. A line segment obstacle is considered to be extending from Ob_1 to Ob_2. The area in green is Zone 0, area in blue is Zone 1 and area in red is Zone 2. Lemma 2.1 thus follows from the figure where the boundary of Zone 0, 1 and 2 are marked by lines extending from the vertices of the obstacle.

For describing the effect of the IR beams, we assume that robot A is transmitting while B is receiving. The second robot B is placed at some arbitrary location in the room.

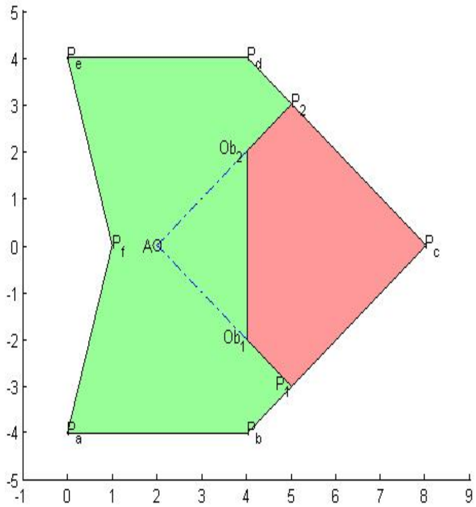


Fig. 3. Absence of Zone 1 in this setting

Depending on the zone that it is placed in, the action it should take will vary. However, we are using only an IR receiver as the sensor and thus the robot itself has no knowledge of the zone it is in. The receiver is capable of recording the direction in which the rays hit it. This direction is then used to orient itself and take further steps. We now present another result that is useful in the development of our algorithm.

Lemma 2.2: All the consecutive zone numbers till R_n (the reflective index) need not be present in S.

Proof: The proof is by contradiction. In particular, assume all the consecutive zone numbers till R_n are present in a region S. Now consider the region shown in Fig. 3. The boundary of region S and the location of obstacle are such that there cannot exist any subset of S that qualifies as Zone 1. Thus S only contains Zone 0 and higher zones. The reflective index R_n is 3 in this case. Thus, all the consecutive zones do not exist in S. Q.E.D.

Theorem 2.1: In a given region S, let there be n zones with k deficient zones. The zones in increasing order are adjacent to each other and IR beam enters a zone i through one of its immediate (prior) zones.

Proof: Let the zones be numbered $Z_1, Z_2, ...Z_{i-1}, ...Z_{i+1}, ...Z_n$ with k missing zones. Let a polygonal region A be defined such that the polygonal edges of this region are due to the reflections sliding through the edge or vertex of an obstacle. It follows from Lemma 2.1 that the IR beam that slides along the vertex of an obstacle divides the region into two halves with different zones. One half consists of rays incident from beyond the obstacle and thus with a zone number say Z_i. The other half cannot have any rays incident in the previous manner due to the obstacle itself. However, IR beam comes to this region due to multiple reflections from other walls or obstacles. This gives the other half region a new zone number Z_j. Thus, by construction, $i < j$. Additionally, if there is more than one way of approaching this second region like $Z_{j1}, Z_{j2}, ...$, we define the zone number with the lowest of these values. However, the lowest of these values will still be greater than Z_i. Thus, if Z_{k-1} and Z_{k+1} are consecutive zones (in other words zone Z_k does not exist), they have to be adjacent to each other. The second statement of Theorem 2.1 is a consequence of this result. Since zones with increasing zone value are adjacent to each other, any ray entering a zone with higher value will have to come through a zone with lower value. Q.E.D.

Remark 2: Taking Fig. 2 as an example, let the region A be defined by the $\triangle\ P_7 P_{11} P_{12}$. It can be noticed from the figure that each edge of A is a consequence of IR beam grazing along the vertex of the obstacle. Additionally, these beams divide the space into two halves one from each zone. The zone in blue is Zone 1 and zone in red is Zone 2. In the case of any overlap of zones, the zone is given a number with lower value. Thus the regions $P_2P_5P_{12}P_{11}$, $P_5P_{10}P_{12}$, $P_7Ob_2Ob_1P_{11}$ are reverted back to Zone 1 in spite of being capable of having an IR beam with two reflections reaching it.

It follows from Lemma 2.1 and Theorem 2.1 that the IR beam grazing the vertex of an obstacle can create a change of zones in a consecutive manner. Thus a robot can always move from Zone Z_i to Z_{i-1} (if it exists or else the next lower zone) in a straight line path.

III. Proposed Algorithm for Rendezvous

The proposed algorithm involves adaptation of the robot to the surroundings especially in view of IR beacons on-board the robot. Further, we need an algorithm that determines the direction to be chosen for motion of a robot. Therefore, sub-algorithms for adaptation and action (direction determination) are presented first. This is followed by the main algorithm for rendezvous.

A. Adaptation Algorithm

In the rendezvous problem with IR beacons, as the robots plan and move towards each other, the transmitters and receivers of the robots should not interfere with each others' functions. The adaptation algorithm helps to know the bound on time after which a signal would die down (go below the detectable level of the receivers). With the help of this bound, we can turn on the transmitter of one robot along with the receiver of another. After the time given by the adaptation algorithm, the receiver of one robot can be turned on along with the transmitter of another. In this way, by alternating their signals and understanding the directions, the two robots achieve rendezvous. Another common issue in dealing with IR beacons is the ambient lighting conditions. Depending on the illumination of the room and the reflective surfaces, the IR beam can die down sooner. With the help of adaptation algorithm, the receivers are normalized to a certain value. This helps the beacons to adapt to any given ambient lighting conditions.

As mentioned earlier, the two robots A and B are each assumed to have six transmitters and six receivers to cover the entire range of 360°. The IR beam originating from these transmitters reflects off various obstacles, walls and other surfaces. If the receiver of the same robot is turned on during this time, the reflections create an illusion of another robot being present in the direction of the obstacle or wall.

Algorithm_Adaptation
Input: minimum distance 'ϵ' between the two robots after rendezvous in cm
Output: $T_v(A)$ and $T_v(B)$
1: **for** each robot A and B
2: Divide 0° to 360° into six directions
3: **for** each of the six transmitting directions of the current robot
4: Turn on the transmitter and all the six receivers
5: Turn off the transmitter with the first ping in any of the six receivers
6: Measure the number of pings at all six receives and store them in P_1, P_2,...P_6
7: Measure the time taken (from the first ping) and the direction for the last ping and store it in t_i where i is the current direction number of the transmitter
8: Calculate ϕ as the average of P_1,...P_6
9: Compute the threshold value for the current direction with the help of the following formula:

$$T_{vi} = \frac{\phi(1 + \frac{1}{\epsilon})}{2} \tag{1}$$

where ϕ is computed as given in Step 8 and
ϵ is the desired distance (in cm) between the two robots after rendezvous
end for
end for
10: Compute $T_v(A)$ and $T_v(B)$ as the average of $T_{v1}(A)$....$T_{v6}(A)$ and $T_{v1}(B)$....$T_{v6}(B)$ respectively
11: **Return** $T_v(A)$ and $T_v(B)$

Remark 3: The adaptation algorithm removes the necessity of centralized control and any form of communication between the two robots. The robots now work in the intervals of $T_v(A)$ and $T_v(B)$ thus ensuring that there is no signal overlap.

B. Algorithm for Determining Direction of Turn

After calibrating the ambience in a given room, we determine the direction of motion. The direction of travel for each robot is determined by the direction in which the IR beam from the other robot hits it first. We now present Algorithm_Action that determines the direction of the next step for both the robots.

Algorithm_Action

Input: Threshold values $T_v(x)$ and $T_v(y)$; x is the transmitter robot and y is the receiver robot
Output: The direction of movement for x and y; D_x and D_y respectively. The time of travel for opposite IR beams from x and y; R_x and R_y respectively.

1: Initialize all transmitters on x and all receivers on y.
2: Turn off the transmitter on x after time $T_v(x)$.
3: Wait for the first ping of IR pulse on any one of the receivers of robot y. Store the direction in D_y and the time after initialization in R_y. Turn off the receiver on robot y.
4: Initialize all transmitters on y and all receivers on x
5: Turn off the transmitter on y after time $T_v(y)$
6: Wait for the first ping of IR pulse on any one of the receivers of robot x. Store the direction in D_x and the time after initialization in R_x. Turn off the receiver on robot x.

C. The Rendezvous Algorithm

The algorithm first detects if the minimum distance 'ϵ' of rendezvous given as an input is feasible or not. If it is not, it requests to restart the algorithm with a new 'ϵ'. If it is, it begins with the *Algorithm_Adaptation* which is non-recursive. Once the threshold values are available, Algorithm_Action is employed to move the robots towards the point of rendezvous.

Algorithm_Rendezvous
Input: The diagonal length of the robots A and B, l_A and l_B respectively. The minimum distance between the two robots after rendezvous.
Output: Report if rendezvous is not possible due to improper 'ϵ' else achieve rendezvous.

1: **if** $\epsilon < (l_A + l_B)$
2: **then return** minimum distance 'ϵ' will cause collision
3: **else continue**
end if
4: Compute ($T_v(a)$,$T_v(B)$) using Algorithm_Adaptation
5: Initialize two variables R_A and R_B to infinity
6: **while** the individual threshold values of A and B are smaller than R_A and R_B
7: Compute (D_A,D_B,R_A,R_B) using Algorithm_Action
8: move robot A in the direction of D_A by l_A and robot B in the direction of D_B by l_B
end while
9: Initialize the Ultrasonic sensors on both robots A and B and detect the distance between each other in variables d_A and d_B. Note that d_A=d_B.
10: **while** $d_A > \epsilon$
11: move robot A in direction d_A by l_A and B in direction of d_B by l_B
end while
12: **return** robots achieved rendezvous

D. Correctness of Algorithm_Rendezvous

The first part is the adaptation. In the adaptation phase, a simple averaging technique is used to compute the levels beyond which the IR beam is detectable without any interference from ambient light sources. In the second part of the algorithm, we have rendezvous in an iterative manner. It follows from Theorem 2.1 that an IR beam enters the region of a robot through its prior zones. Thus, turning the robot towards the direction in which the IR beam is incident and moving it by a fixed distance guarantees that the robot moves in the direction of decreasing zones. The comparison with ϵ ensures that the algorithm terminates in a finite number of steps.

Remark 4: The zones change due to the vertex or edge of an obstacle as given by Lemma 2.1. Therefore, it is possible that the robot goes and hits the obstacle either at its edge or its vertex. To avoid this, we use an iterative algorithm. An iterative algorithm would change the direction of the robot as soon as it changes zones thus making sure that it never hits an obstacle or a wall. This can be observed from Fig. 3. As the robot moves from Zone 2 to Zone 1, the robot gets its IR beam from a different direction altogether. For example, if the robot is now located in the triangle $\triangle P_2P_{11}Ob_1$ which is of Zone 1, the IR beam would hit the wall of P_aP_d and reach this zone. So, the algorithm would direct the robot to move towards the wall P_aP_d. However, as soon as the robot crosses the imaginary line P_2Ob_1, it enters into zone 0. The IR beam would now be incident directly from A. Thus the robot orients itself towards A and moves until Rendezvous.

The dynamics of the robots do not form a part of the algorithm. Thus robots of heterogeneous nature can be used with this algorithm. Since Algorithm_Rendezvous ensures that the minimum distance for rendezvous is greater than $l_1 + l_2$(the sum of diagonal lengths of the two robots in the traveling direction), collision of robots is also not an issue.

IV. Experimental Setup and Results

In this section, we present the results of our experiments with a bipedal robot and a mobile robot. Both these robots were fabricated indigenously. The details of the robot and the IR beacons are presented first.

A. Experimental Setup

The mobile robot is shown in Fig. 4(a). It has two differential drive wheels at the back and two castor wheels at the front. The robot can handle a payload of 5 kg and is powered by 1000 rpm motors. A Polulu driver board [8] is used to control the robot using an ATMEGA 32 micro controller.

The bipedal robot is shown in Fig. 4(b). This bipedal robot is unique due to the absence of knee joints. They have conventionally been called compass gait bipeds. However, compass gait bipeds have pointed feet without any place for movement. We designed two feet to increase the stability of the biped. The feet thus bend sideways and the hip joints swing forward and backward. The algorithm to walk the biped is thus straightforward. The biped is bent at its ankle joint (sideways) shifting its weight on to one foot. The other leg is swung forward and the robot is brought back to its standing position. Due to the design of the biped and the dimensions of its foot, the biped swings forward pulling its weight onto the second foot. The biped is then swung on the second ankle and thus the algorithm continues to achieve continuous motion.

The biped achieves a sideways gait using a gait employed by ice skaters. They keep one foot on ice and swing the second. By the principle of conservation of angular momentum and due to the negligible friction on the surface of ice, the skater turns around on the stationary foot. We use the same principle to rotate the biped. Since we are dealing with non conservative forces, the rotation of biped is not predictable. And since we are not using any motors to achieve the same, we cannot make use of any encoders. However, due to the strength of the algorithm, the direction of the robot is handled by re-calibrating it continuously. This reduces the hardware necessary as well as the computational effort.

We use Polulu IR transmitter-receiver pairs (transceivers) [9] for the IR beacons. Each Polulu transceiver uses six transmitters and four receivers. Fig. 4(c) gives a picture of the hardware. Each transmitter covers 60° while each receiver covers 90°.

B. Experimental results

The receivers and transmitters on both the robots first go through the adaptation mode.

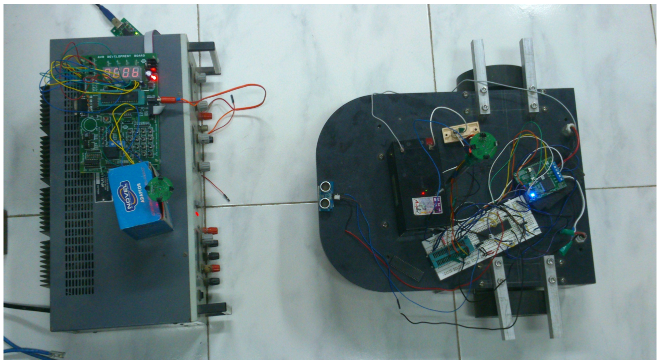
Having calculated T_v, for both the robots, they individually start the transmission and reception of signals in pre-allocated time intervals.

The receivers of the Polulu IR transceiver are labelled as North, East, South and West. The robots rearrange the signals coming from various directions to one of these four directions and then go on with the algorithm.

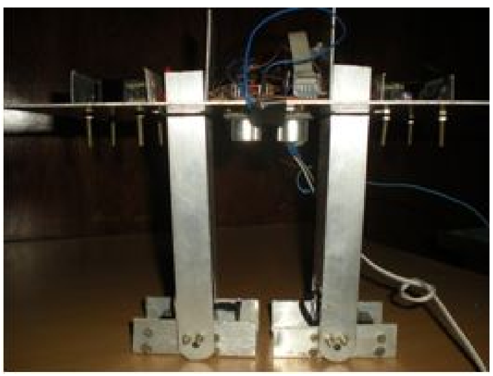
The step length of the biped is just 5 cm while the mobile robot can cover 100 cm in a couple of seconds. Due to this huge difference in speeds, we designed the biped to transmit and receive at a much faster rate and update its direction as compared to the mobile robot. Thus the biped moves continuously until there is a necessary rotation.

It can be noted that the IR beacons on both the robots are placed at the same level from the ground to ensure proper transmission and reception of signals.

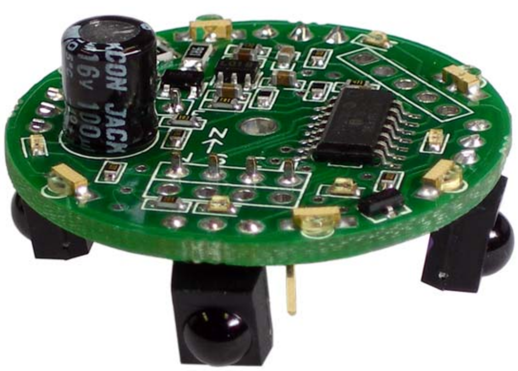
Fig. 5 gives various locations of the robots before they could achieve rendezvous. The mobile robot identifies the direction of IR rays hitting it from its front. Thus it moves front by its fixed distance l_1 and reaches the position in Fig. 5(a). The rays continue to hit it from the same direction and thus the robot moves further. It then rotates right and moves closer to the biped. When the mobile robot is close to the cardboard box, the rays come from around the box. The robot now rotates again toward the direction of the incident signal which is to its left. This is shown in Fig. 5(b). It now moves forward by its prescribed amount to get in complete view of



(a) Mobile Robot



(b) Bipedal Robot



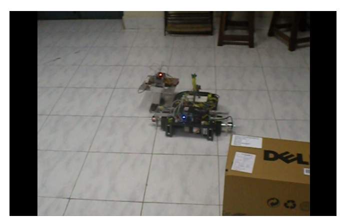
(c) IR Transceiver

Fig. 4. Hardware used for the experiment

(a) Mobile robot prior to turn

(b) Biped and mobile robot closer

(c) Mobile robot after negotiating an obstacle



(d) Rendezvous achieved

Fig. 5. Different positions leading to rendezvous

the biped. However, the biped now stands to its right and thus the robot turns right facing the biped. This is shown in Fig. 5(c). Fig. 5(d) shows the movement of the two robots to their final position.

V. Summary

In this paper, we have considered the problem of rendezvous between a pair of robots with limited communication. In particular, we have assumed that the robots carry only IR beacons. We have discussed issues pertaining to IR signals and derived some important results. We have then presented an algorithm for rendezvous taking care of the ambience. We have established the correctness of the algorithm. We have also described experiments on rendezvous between a mobile robot and a bipedal robot fabricated indigenously. The work can be extended to handle more than two robots.

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