SUPPORT FOR ROBOT DOCKING AND ENERGY FORAGING
A Computer Vision Approach

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Abstract: Swarm robotics deals with the multi-robot coordination for achieving the common objective. The latest research in this field focuses on more complicated domain of problem where swarms of robots may require to physically dock together to achieve the goal. The physical docking may be required to move over a big obstacle or also to perform precise physical connection with certain objective e.g. battery charging. In this research, the information from vision sensor is considered to provide support for performing precise physical docking. The robotic system considered in this study requires the robots to autonomously recharge their batteries for guaranteeing long term operations and also to perform complicated physical docking for which precision is necessary. A very simple but effective solution based on LEDs, used in a specified pattern on docking station, is adopted. The approach presented in this research is found computationally less expensive so is suited to be used with swarm robotic system which uses small robots with limited memory and processing resources.

1 INTRODUCTION

In swarm robotic systems, where multiple robots try to achieve tasks collectively, the robots may require to work continuously for several hours to achieve a common goal. The biggest constrained to the continuous operation is the limited on-board power. If robot runs out of battery and leave a mission while performing collective task, then it can result in mission failure. One way is the manual charging or human intervention for recharging robot, but this may be not possible in hazardous environments (e.g building infected with virus or factory with gas leak). In manual charging, as the human assistance is always required so this also prevents the long term autonomous robotic operations which may continue for several hours. The power constraints in robotics introduces the concept of autonomous battery recharging by robots. This requires the robots to determine when they are running out of battery charging, look for the energy points and dock to them for battery recharging purposes. In swarm robotic systems, as many robots are involved, so the provision of limited charging points may also require the robots to dock to each other for energy sharing. The capabilities of energy sharing and battery charging will help the robots in a swarm to ensure long term autonomy and also to show efficient energy utilization by sharing energy resources with each other.

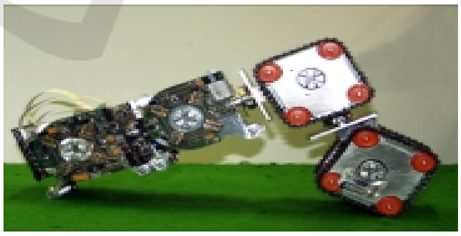

Figure 1: Swarm of robots (Kernbach et al., 2010).

In this research, a swarm robotic system is considered (shown in Figure 1) in which multiple robotic organisms have the ability to physically dock, share information, energy and computational resources with each other to perform certain tasks collectively (Kernbach et al., 2010). Every robot in the swarm also struggles for survival by searching for energy points and autonomously recharging its battery to guarantee its participation to contribute in a long term operation. If robots units find charging points not in access, then they can use their docking feature to physically join with each other and become a single three dimensional robotic organism so that access to charging points may be achieved. This study presents the research done to facilitate the autonomous robot docking and locating energy points for battery recharging purposes. For precise docking, information from infra-red sensor may be relied upon, but from dis-

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tance, the short range of infra-red sensor does not allow the robots to identify the battery charging points. Here, the power of computer vision technology to help robots to look for the charging points and facilitate the robot docking operation is addressed.

2 STATE OF THE ART

Autonomous robot recharging, also known as energy foraging, is an area of research in the field of swarm robotics which is leading to provide solutions to perform long term operations by multiple robots and is been addressed by a number of researchers in this field. In (Schmickl et al., 2008), a collective energy foraging is addressed in which multiple robots try to look for energy resources collectively. Search of energy resources can be performed using the information only from vision sensor (REPLICATOR, 2008). In (SYMBRION, 2008) (REPLICATOR, 2008), swarm robotic systems are described which can look for energy resources individually or can also share energy resources by docking to each other. For battery recharging purposes, physical docking with energy point is essentially required and researchers have used different approaches to detect these docking stations. In (Silverman et al., 2002), a robot equipped with high performance system, laser range finder and vision sensor is used to provide solution to the robot recharging problem. A cone shape physical docking mechanism is provided. To facilitate the detection of docking port using vision sensor, an orange piece of paper is used as a landmark near the port. This landmark helps the robot to locate the charging point and correct its orientation. Laser beacon used above the charging point also provides major help to guide robot to reach the charging point. This is an expensive solution to battery recharging problem considering the targeted system in which robots with limited resources are used. In (Dunbabin et al., 2008), a colour segmentation approach is used to achieve the coordinated vision based docking of an autonomous surface vechicle with the autonomous underwater vehicle (AUV) while performing the recovery of AUV. Multiple processors are used on-board to perform this task. One processor is used for vehicle control and the second is used to perform vision processing as computationally expensive vision based algorithms were used. This solution can not be used in swarm robotic environment, where each robot has a single processor to perform multiple tasks in parallel. In (Low et al., 2007), a wheel mobile robot is used for vision based docking. For the detection of docking port, a black cardboard was used near to it. A corner detection algorithm was used to detect the corners of cardboard and to perform the robot alignment with the docking port. To achieve this, a high performance system is used on-board to perform vision processing operations. As mentioned before, for autonomous battery recharging, physical docking is required and this concept also let the researchers to visualise robotic systems in which multiple robots dock together to become a single robot. In (Zhang et al., 2011), a modular self-reconfigurable robotic system is considered and infrared sensor based robot docking is addressed, but the limited range of infrared sensor does not allow the robots to detect each other from large distance. The use of IR together with vision information is also addressed by several researchers. In (Will and Shen, 2001) (Nagarathinam et al., 2007) only IR sensor information relied on to perform docking. The use of only vision support for docking is presented in (Bonani et al., 2005) (Yamakita et al., 2006) (Trianni et al., 2009) in which swarm of robots dock together to drag heavy objects. This is an example of a swarm robotic system which addresses the problem where an object appears to be too big that a single robot alone can not move it and requires the support from other robots. The docking ports used on these robots are very simple and does not required precise aligment. In (Kurokawa et al., 2006) (Sastra et al., 2007), a more complicated docking mechanism is presented which uses help from IR and vision sensor to attach two robot with each other.

3 METHODOLOGY

As discussed before, in the considered system, the robots have an ability to dock with each other. For this purpose, a complicated mechanics to enable hardware docking is addressed in (Kernbach et al., 2010) and is also shown in Figure 2a. This system requires precise alignment of the robot units to perform successful docking. Infra-red sensors can provide precision but their short range does not let this approach to be effective when robots are far from each other. To easily identify the robot docking port using vision, four LEDs are mounted on the port as shown in Figure 2a. The robot will turn ON its LEDs to request the other robots to start docking operation. For the demonstration of the algorithm providing vision support for docking, SRV robot by Surveyor Corporation was used as it uses the same Blackfin processor which is used in robot units shown in Figure 2a. To represent the other robots docking port, a white box with four Red LEDs mounted on it was used. Here, the target is to develop light weight vision algorithm which can

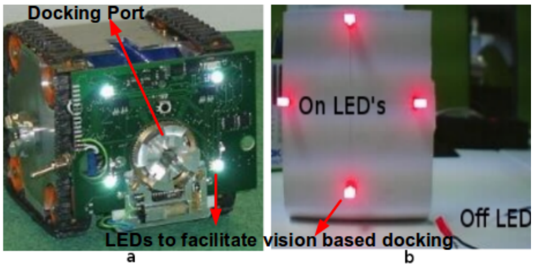

Figure 2: (a) Docking port and LEDs to facilitate vision based docking. (b) Dummy docking port.

run in real time on small size robot. As this algorithm will be running all the time (when docking is required) in parallel with the other computationally expensive algorithms (e.g. scene understanding) and multi-robot communication algorithm, makes the task more challenging. To address this problem, a colour blob detection based approach to identify the ON LED's in the known pattern was developed. The following observations complicates this task.

1. OFF LEDs will be detected as red blobs in the image. However, in ON state, their centre appear red to human eyes but white to vision sensor as shown in Figure 2b. A red LED in OFF state is also shown for comparison.
2. As robots have only one camera and when close to the port, LEDs go out of its vision, so alignment upto some distance from port is possible. On getting very close, support from other sensors (IR) would be required.
3. While approaching the blobs, the pattern can be very titled depending on the direction and angle of approach.

Based on these observations an algorithm is required which also gives certain level of confidence to drive the robot in the right direction to perform docking. The problem is therefore divided into a number of processing steps which reduces the complexity in every step while not sacrificing the performance. The following processing steps are taken.

3.1 Blob Detection of LEDs in ON State

Implement a colour blob detection algorithm to detect red blobs in the current image. This algorithm directly processes the YUV images. In YUV format, Y provides luminance, whereas U and V provide the chrominance information (shown in Figure 3a). In the current implementation, V values greater than 190 and U less than 200 are selected. In Figure 3a, the range of UV values used to detect red blobs are identified by the black boundary. U values greater than 130 seems not required but its use makes the algorithm less sensitive to change in the lighting condition.

To show the performance of algorithm to detect red LEDs blobs, image shown in Figure 2b is processed. This image, captured by the robot vision system, shows four red LEDs in ON and one in OFF state. The output of blob detection algorithm (also processed by the dilation algorithm to fill small holes in the blobs) is shown in Figure 3b. The blobs caused by both ON and OFF LEDs are detected. To determine the blobs from ON LEDs, the brightness information from YUV image is utilized. By thresholding the Y image and using it together with the output of blob detection algorithm, the blobs caused by LEDs in ON state are identified and are shown in Figure 3c.

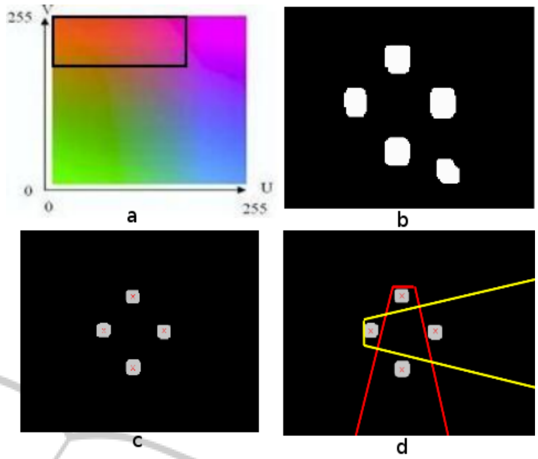

Figure 3: (a) UV plane. (b) Output of blob detection algorithm. (c) Blob statistical information. (d) Search field for neighbouring blobs.

3.2 Obtaining Statistics of LED Blobs

To obtain the statistical information of the LED blobs, the image shown in Figure 3c is processed by the algorithm. The image in Figure 3c is a binary image in which 0 value is representing the dark part and 1 is representing the detected blobs. All the blobs are appearing as a separate segments. The algorithm performs segmentation (using Flood Fill approach) of the image and assign a unique ID to each segmented region. This ID information helps determining the centroid of each blob, hence provides the statistical information of the blobs. The centroid of the blobs are marked with cross sign in Figure 3c.

3.3 Classification of Red LED Blobs

After determining the statistics, blobs satisfying the required pattern are classified as Top, Bottom, Left and Right LED blobs. The classification algorithm makes a reasonable assumption that while scanning the image from top to bottom, the first blob found is most likely to be from the Top LED following some conditions. Otherwise, the rest of the blobs will be checked one by one. These conditions are as follows.

- Around the currently assumed Top blob, a cone shaped search field is defined as shown in red colour in Figure 3d. In this field, the algorithm try to locate the Bottom blob. Some checks are made to avoid the blobs resulting from reflection of Top LED to be considered as Bottom LED blob. The bottom blob should not be detected very close to the top blob. In the current implementation, it is defined to be detected at-least 20 pixels down from the top blob and the blob size in pixels should be almost same as the top blob. Here, 20 pixels limit was determined empirically for QVGA resolution in which processing is done.
- Once the top and bottom blobs are found, then their centre point is determined. Across this centre, 60 pixels wide search field is defined. The blob which is found on the left side of this search field is most likely the blob resulting from left LED. Then again, a cone shaped search field is defined, extending in right direction (shown in yellow colour in Figure 3d). Algorithm search this field to look for the blob resulting from right LED.

3.4 Control Algorithm

Flow diagram of control algorithm is shown in Figure 4. It performs following sequence of operation.

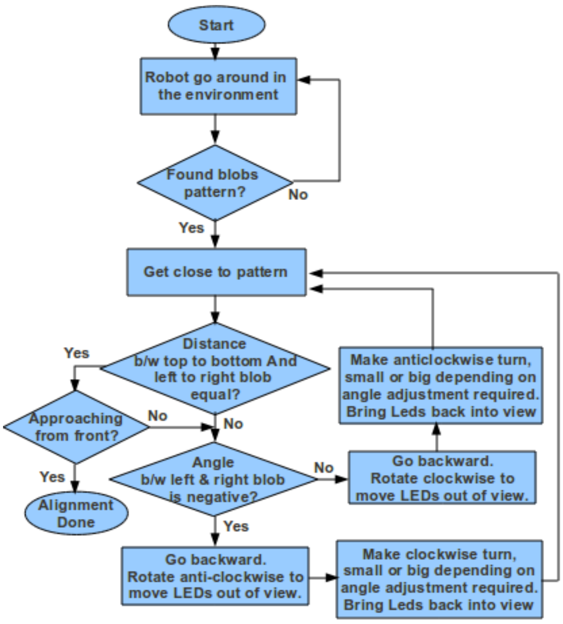

Figure 4: Flow diagram of control algorithm.

- Move robots in the environment and search for the blobs in the required pattern. On finding the pattern, the algorithm performs the blobs classification. As there is a strong possibility that the robot is not approaching the LEDs from the front but at some angle and this angle could be small or large (can not be identified clearly from distance), so rather then performing alignment in the first go, the robot first tries to get close to the blobs.
- If the distance between Top to Bottom and Left to Right blobs are equal and robot was approaching from front, then robot assumes that the maximum precision is obtained using vision and control algorithm stops there. Otherwise, the robot determine the direction of its approach.
- If the robot is approaching the LEDs from left side with reference to the LEDs locations, then the LEDs pattern will appear as shown in the figure 5a. The right LED blob will make a negative angle with the left blob. The control algorithm will move the robot backward, rotate it anticlockwise so that the LED blobs go out of its vision. Then the algorithm will move the robot to make a clockwise turn. How big is the turn? It depends upon how big is the angle adjustment required. It will keep on making this turn until the LEDs are back into its view field. Then it will move the robot again towards the blobs to see the further correction required.
- On the other hand, if the robot is approaching from right side then the LEDs pattern will appear as shown in the figure 5b. The right blob will make a positive angle with the left blob. The control algorithm will move the robot backward, rotate it clockwise and then makes an anti-clockwise turn to bring the LEDs back into view. This process continue until the robot align itself.

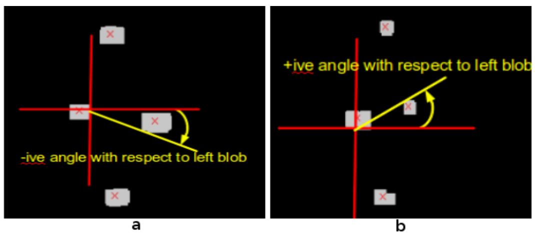

Figure 5: (a) Robot approaching from left side. (b) Robot approaching from right side.

4 RESULTS

Using the approach presented in methodology section, some experiments are performed to do robot alignment with the docking port. Results from four of these experiments are shown. In Figure 6 the starting position of robots, before alignment, is shown. In Experiment 1 and 2, the robot is less misaligned but in experiment 3 and 4, robot requires more alignment as it is approaching the LED's with a very sharp angle.

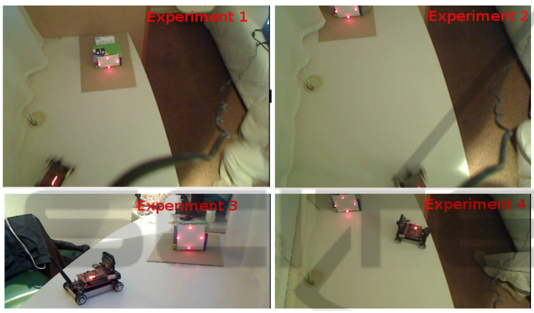

Figure 6: Initial pose of the robots before alignment.

The trajectory of the robot in experiment 2, is shown in Figure 7a. As the robot is less misaligned with the LEDs, so control algorithm achieved the vision based alignment in less time. In comparison, the result from experiment 4, which requires more alignment, is shown in Figure 7b. In Figure, the different stages followed by the control algorithm to perform alignment, are shown in terms of trajectories followed by the robot in different colours. In the begining, the robot approached the docking station straight (shown in black) and determines the angle made by the left blob with the right blob. As the angle is large, so it moved back and make a big turn while approaching the port to reduce the error in angle (shown in blue). Finally, the robot was less misaligned so it moved back again and makes a short turn (shown in green). This time the robot was aligned and stops here.

The results obtained from the four experiments, after alignment is done, are shown in Figure 8. In all these experiments, the robots are almost fully aligned with the four LEDs. This is the maximum support which vision can provide in docking. If the robot tries to get further close, then LED's go out of its vision and the robot can not take any further decision. For final mechanical docking and precise alignment, the control can rely on infra-red sensor information.

To demonstrate the functioning of vision based docking support in a swarm robotic environment, an experiment is performed in which a number of robots are looking for docking port collectively. The docking port is installed on one of the robot. The robots are

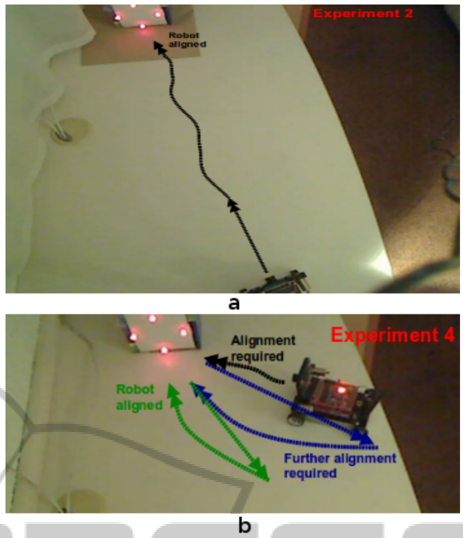

Figure 7: (a)Robot trajectory in experiment 2. (b)Robot trajectory in experiment 4.

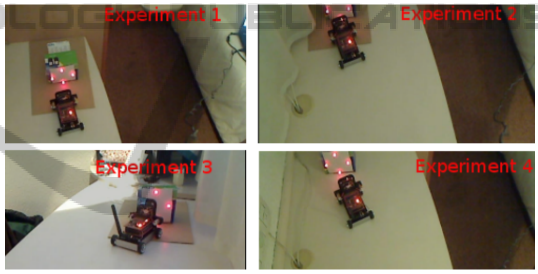

Figure 8: Pose of the robot after performing alignment.

performing vision based obstacle avoidance, sharing information with each other and simultaneously looking for docking port. The robots are performing this task collectively that is, when a robot in a swarm will find the docking port, it will inform its team members to stop looking for the docking port and quit the mission. After informing the team members, the robot which finds the docking port, will align it self with the docking port using vision so that docking operation can be facilitated. Several tests are performed using this approach. In Figure 9, one of the experiment is shown. Three robots are used to perform the collective search operation. In the begining, the LEDs used on the docking port of the robot are turned OFF as shown in Figure 9a. The robots start the mission with vision based obstacle avoidance, searching arena for docking station and in parallel, also informing each other whether any of them have found the docking port. Finally, one robot finds the docking port, it inform the other team members that they are no longer required to search for the docking station, and align it self with docking station as shown in Figure 9b. All the other robots leave the search operation. It can be noticed that, this vision based docking support may be used for the docking of two robots, so that they can become a single robotic organism. Or it can be used for docking with the energy source so that battery recharging operation can be performed.

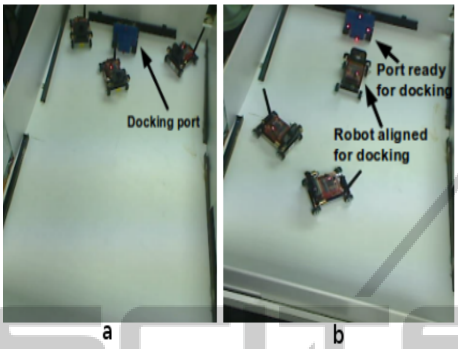

Figure 9: (a) A collective search for docking port (b) One robot finds the docking port and the rest quit mission.

5 CONCLUSIONS

In this research, a simple but effective approach to support the robot docking and battery recharging operation using visual information is provided. Successful experiments demonstrating the precise alignment of the robot with the docking port are presented. This approach enables the detection of the docking port even when the robots are placed far from the docking station. Whereas approaches using other sensors such as infrared, are able to perform docking only if the robot is very close to the docking port. For the detection of the docking port, as this approach is using LEDs in a specific pattern which are very prominent in the environment. So this enables the approach to perform well even in the cluttered environment. From the experimental results obtained from this research, it is concluded that, the idea of using visual information to perform docking, may be extended to use with more complicated robotic systems which are design to perform planetary exploration and which may require physical docking for sharing energy and computational resources.

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