Active Perceptual Anchoring for Enhancing the Perception of Cooperative Mobile Robots

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***Abstract*— In this paper, we describe a system for controlling the perceptual processes of two cooperative mobile robots that addresses the issue of enhancing perceptual awareness. Here, perceptual anchoring enhances the awareness of the system by employing an anchor-based active gaze control strategy or active perceptual anchoring to control the perceptual effort according to what is important at a given time. Through anchoring we extend the notion of awareness as knowing what the symbols in the control module represents to by connecting them to the objects or features in the environment. We demonstrate the present system through a simulation of two nonholonomic mobile robots performing a cooperative transportation by carrying a cargo to a target location where there are two other robots moving around. The system is able to efficiently focus the perceptual effort and thus able to safely carry the cargo to the target position.**

I. INTRODUCTION

Consider a situation depicted in Fig. 1, which shows two robots cooperatively transporting an object to a certain destination. Each of the robots equipped with a panned camera system. To implement this system, one can easily identify the problems that must be addressed carefully at the software level, e.g., recognition; each robot must be able to recognize landmarks to estimate its position and to aid its navigation system, and must be able to recognize other moving robots or objects and know their position in order to avoid collision. However, each of the robots can only view a fraction of the environment at any given time. This is dictated by the limitation of field of view and range of the sensor. In conventional approach, if the sensor of one robot is focused on one particular object the robot will then loose its awareness of the other objects in the environment. Therefore, each of cooperative robots should have a facility that allows them to be aware of the important details of the environment despite off the sensors limitation.

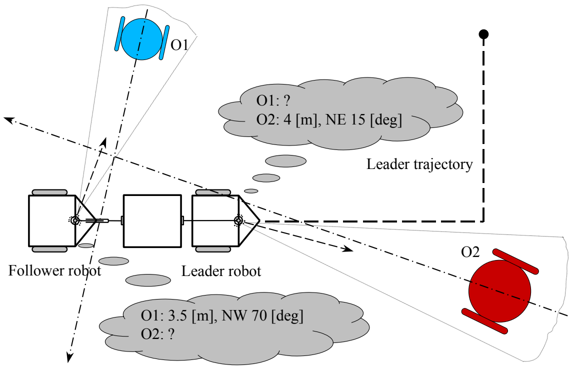

Fig. 1. Cooperation in a dynamic environment.

This paper focuses on developing a formalized approach to awareness, particularly for decentralized cooperative mobile robots. Specifically, the designed of the architecture used for awareness was highly influenced by the need of separating the action processes and perceptual processes while maintaining some interaction between the two. This requirement is essential in view to the fact that whole system is design for performing some task other than monitoring and sensing.

Recently, the interest in cooperative robotic systems has grown significantly (e.g., [1], [2], [3], [4], [5]). The primary reason for this growing interest is the recognition of the large number of application domains in which cooperative robotic systems is applicable in; military applications such as surveillance, reconaisance, and demining; industrial applications such as cleaning, earth moving, and transportation of large objects; and underwater and space exploration applications, such as pollution monitoring, rock gathering and search for water in other planets. Advantages that can be achieved in using cooperative teams of robot include increase robustness through redundancy, decrease in mission time completion through parallelism, and a potential to reduce the individual robot complexity through heterogeneous robot teams.

Despite convincing results shown in [6], [7], [8], none of them explicitly tackle the case of awareness for a cooperative mobile robot as a problem of controlling the perceptual effort. To be specific, the agents in [6], [7], [8] where designed to perform purely observation related task. As stated above, the range of cooperative robot application is beyond constructing simple observation or surveillance systems. In some applications, such as decentralized cooperative mobile robots that cooperatively transport a cargo in Yang et al. [9], [10], there is a need to separate the process of controlling the perceptual effort from some action processes of the cooperative behavior, while maintaining some form of interaction between the perceptual and action processes so as to allow the perceptual processes to efficiently conform its objective for the needs of the cooperative behavior. Here, the present awareness is defined as knowing the position of other robots in the environment. The notion of awareness is then extended to knowing what each of the symbols (i.e., symbols in a controller) means or it represents to — that is

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anchoring symbols to perceptual data that correspond to the actual objects or features in the environment [11], [12], [13]. This new notion of awareness allows each robot to remember the position of other robots in the environment and does not just rely on fresh inputs from sensors or information from other robots passed through a communication channel. Each agent controller is composed of two module namely the navigation control module (NCM) and the perception system module (PSM). The PSM employs an active perceptual anchoring (APA) strategy [14]. The goal of employing an APA strategy is to enhance the perceptual awareness of the system by actively controlling the perceptual effort of a robot sensor. A finite state machine that actively controls the focus of attention with the help of anchoring realizes the APA.

II. A DECENTRALIZED APPROACH

Figure 2 shows a decentralized system for two cooperative mobile robots, R_1 and R_2. Two major components are visible in the figure: the navigation control module (NCM) and the perception system module (PSM). The NCM is in charge of generating control commands related to navigation and for cooperation with its partner robot. On the other hand, the PSM is in charge of controlling the perceptual effort of the system and consequently responsible of giving the awareness capability to each of the cooperative agent. The PSM will generate control command to change or track the current focus of attention. A more detailed look of the PSM is shown in Fig. 3. The PSM includes an APA part and anchors. Anchors are simply data structure so that each anchor can contain several type of information pertaining to a particular object (or feature) in the environment. The NCM is supplied with information from the anchors by grounding each symbols with its corresponding objects (or features) in the environment through the anchors. The NCM has the ability to tell the PSM as to what are the important objects (or features) at the current time by passing the $needed$ measures of each symbol to the PSM. And in response, the PSM will ensure that those symbol–object connections are maintained by keeping the information in the anchors updated. Furthermore, there is a wireless communication connecting the PSM of the two cooperative robots to allow the two cooperative agents to share the information that they are aware off.

III. ACTIVE PERCEPTUAL ANCHORING

The concept of APA yields the effect of combining together two popular approaches to perception control. One is the approach of packing together the perceptual and action processes into one module (or behavior) and another is the approach of using information about the current task to perform an active control of the agent's sensor [15], [16], [17], [18], [19]. The purpose of the former is to focus the perceptual effort exclusively on those features in the environment that are relevant to the current task. The latter, is to actively control the agent's sensor that will allow the agent to search for features in the environment. Such an active control means selecting a specific algorithm or physically pointing a sensor in a specific direction; the concept of the active control was initially presented in [20] and presently it remains as one of the active research areas in computer vision [21].

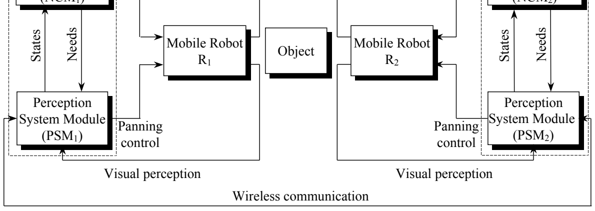


Fig. 2. Decentralized control strategy.

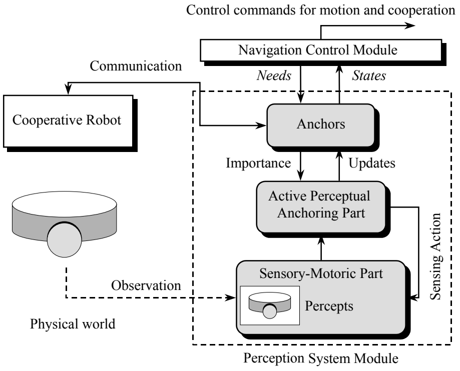


Fig. 3. Details of the perception system module (PSM).

The main advantage of employing APA and anchors in the PSM is that the APA part can use the information from the anchors to choose which among the objects (or features) in the environmnet will be the focus of attention and can narrow down the search process. Each anchor can contain several types of information that best describe the state of the object that it represents. Conforming to our definition of awareness as knowing the position of objects in the environment, an anchor will contain data such as the relative orientation and distance from an observing robot to the object. As in [14], each anchor will also contain an $anchored$ value on [0,1] scale, which measures how recently the anchor was actually anchored (i.e., updated) to the real object in the environment. Moreover, each anchor will also contain an $importance$ value which measures how important an anchor is to the PSM. For instance if the $importance$ values in the anchors indicate that a certain object needs to be monitored at the present time, the APA part can simply use the estimated values of properties (e.g., relative position and distance) stored in the corresponding anchor to estimate the current location of that object in the environment, making the perceptual effort of searching and tracking the object more efficient. Moreover, the PSM will

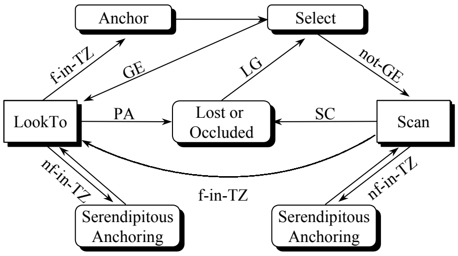


Fig. 4. Active perceptual anchoring system.

receive a $needed$ measure for each symbol from the NCM. The needed measure is a gauge that tells which among the objects is vital to the current state of the NCM. By allowing the NCM to pass the needed measure to the PSM and by making the important measure dependent on the needed measure, the perceptual effort generated by the PSM will be made relevant to the current state of the NCM. The importance measure is computed based on the needed measure and the anchored measure.

In the preceeding section we introduced our cooperative mobile robot platform, in which we considered two mobile robots that cooperatively transport a cargo by carrying it to a desired destination (Figure 1 will give a good illustration of the scenario). Moreover, the working environment is cluttered with two other moving robots. Therefore, each cooperative agent is required to have the ability to avoid colliding with those two other robots working on the same environment. Here, if the NCM of a cooperative agent is not on obstacle avoidance mode, the PSM will select the anchor with the highest $importance$ value to be the focus of attention. For a given anchor a in S, where S is a set of anchors, we represent the important measure of a as

$$important(a) = needed(a)[1 - anchored(a)] \tag{1}$$

where $needed(a)$ is the needed measure of a and $anchored(a)$ is the anchored value of a.

If the NCM is on obstacle avoidance mode, the PSM will only use the $needed$ measure from the NCM to select the next focus of attention. The NCM must be supplied with fresh and accurate information of the most threatening object in the environment. In our simulation study, the $needed$ value for non threatening object is set to 0.5 and 1 if it is so closed. Moreover, the $anchored$ value for newly updated anchor is set to 1; otherwise it is reduced by 1 percent every time step.

Shown in Fig. 4 is a finite state machine that represents the processes of the APA part of the PSM. The finite state machine generates a sensor control command that can actively point the panned camera to the (new) fixation and will update the information in the anchors with percepts from sensor. The details of each process are given as follows: 1) Select: choose an anchor x to become the new focus of attention of the panned camera. Set the fixation to the expected relative orientation of x. If the $anchored$ level exceeds above from a given threshold, exit via GE (good estimate); otherwise, exit via the not-GE transition. 2) Scan: perform a visual scan to explore the part of the space where x could be located. In our simulation, exploration is conducted by augmenting a search factor to the expected orientation of x, and set the fixation to this value. Exit when one of the followings occurs: a) If an object is detected along the TZ (tracking zone) that matches x, set the fixation of the camera to the relative orientation of the object and exit via f-in-TZ (found in TZ); b) If an object that matches an anchor other than x is detected along the TZ, exit via nf-in-TZ (not found in TZ); c) If the physical scan is completed, exit via the SC (scan complete). 3) LookTo: turn the camera to the current fixation, when: a) If an object that matches x appears within the TZ, exit via f-in-TZ; b) If an object that matches an anchor other than x appears within TZ, exit via nf-in-TZ; c) If the desired orientation of the camera has been achieved and no object is detected that matches x, exit via PA (position achieved). 4) Anchor: measure the (relative) orientation and distance of the object and update the x anchor associated with the object; and select a new focus. 5) Serendipitous anchoring: if an object other than the one represented by x is in TZ, measure its (relative) orientation and distance and update the corresponding anchor; and continue to search x. 6) Lost or Occluded: if either Scan or LookTo has been completed without finding the object that x represents, mark x as lost and go via LG (lost and go) and select a new focus of attention.

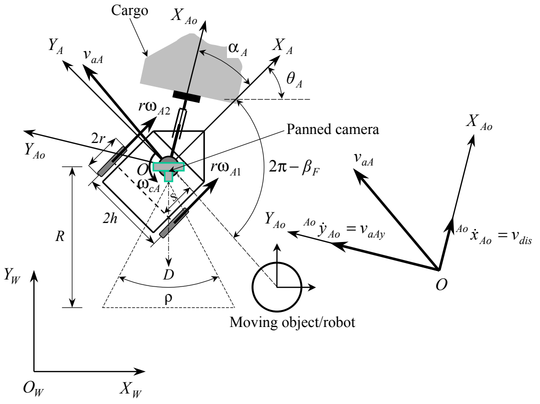


Fig. 5. Kinematic model of the follower robot.

IV. COOPERATIVE ROBOT PLATFORMS

The kinematic models of two mobile robots shown in Figs. 5 and 6, are for the follower robot and the leader robot respectively. The motion of the robot's body is controlled by a differential wheel drive. Much of the platform is tailored from the system introduced by [9], [10] with minor changes. Here, the main difference between the follower and the leader robots is in the construction of the hands. The follower robot's hand is flexible along its length such that its length can stretch or shrink, while the leader robot's hand is rigid. Both hands are assumed to be firmly hooked with the cargo. Moreover, contrary to the system introduced in [9], [10], here, both hands are not actuated and can freely rotate along the reference point O. This means that the orientation and position of the cargo will depend on the position of the two cooperating robot and the distance between them. And thus the length of the follower's hand depends only on the distance between the reference points of the two cooperative robots.

Both the leader and follower robots are equipped with panned camera as the primary external sensor. For simplicity, the sensor region is modeled as a triangle, in which R represents the range of the sensor, ρ represents the field of view of the sensor and ω_c represents the speed of panning the camera. Once an object's reference point is within the area of the triangle, the sensor is assumed to be able to sense and retrieve information regarding that object. In the event that two objects are inside the triangle area, the one closest to the observing robot is assumed to be perceivable and the other one is not; this event is called occlusion. Furthermore, β and I represent the relative orientation and relative distance from the observing robot to an object, respectively.

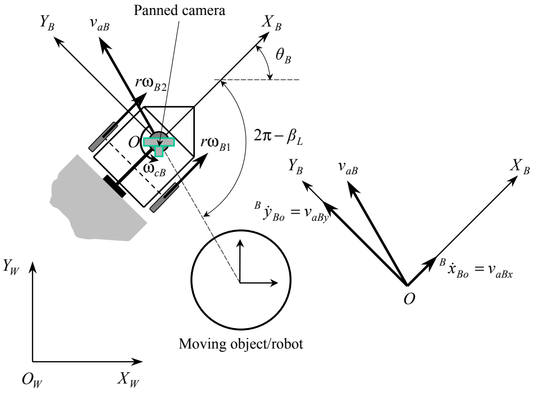


Fig. 6. Kinematic model of the leader robot.

A. Kinematic model

Local coordinate systems $\Sigma_A(O - X_AY_A)$ and $\Sigma_B(O - X_BY_B)$ are set fixed to the frames of the follower and leader robots respectively. Let ${}^A\dot{\boldsymbol{x}}_{Ao} = [{}^A\dot{x}_{Ao}, {}^A\dot{y}_{Ao}]^T$ represent the motion of the follower robot in Σ_A and similarly, ${}^B\dot{\boldsymbol{x}}_{Bo} = [{}^B\dot{x}_{Bo}, {}^B\dot{y}_{Bo}]^T$ represent the motion along space Σ_B for the leader robot. We define $\boldsymbol{\omega}_A = [\omega_{A1}, \omega_{A2}]^T$ and $\boldsymbol{\omega}_B = [\omega_{B1}, \omega_{B2}]^T$ as the angular velocities of the wheels of the follower and leader robots respectively. The kinematic equations for the follower robot are shown below:

$$\boldsymbol{\omega}_A = A_A^{-1}{}^A\dot{\boldsymbol{x}}_{Ao} \tag{2}$$

$$A_A^{-1} = \begin{bmatrix} 1 & h/s \\ 1 & -h/s \end{bmatrix}$$

where $2h$ is the tread and s is the offset of the steering axis from the axle of the wheel.

Equations for the leader robot can be derived easily in the form similar to the above equations. Similar to [12], an additional coordinate system, $\Sigma_{Ao}(O - X_{Ao}Y_{Ao})$, is set fixed to the hand and point O of the follower robot and the motion along this space is given as ${}^{Ao}\dot{\boldsymbol{x}}_{Ao} = [{}^{Ao}\dot{x}_{Ao}, {}^{Ao}\dot{y}_{Ao}]^T$. This additional frame is used for generating cooperation and avoidance control for the folllower robot. Transforming of the motion from Σ_{Ao} space to Σ_A space is performed according to:

$${}^A\dot{\boldsymbol{x}}_{Ao} = {}^A_{Ao}\boldsymbol{R}\,{}^{Ao}\dot{\boldsymbol{x}}_{Ao} \tag{3}$$

$${}^A_{Ao}\boldsymbol{R} = \begin{bmatrix} \cos(\alpha_A) & -\sin(\alpha_A) \\ \sin(\alpha_A) & \cos(\alpha_A) \end{bmatrix}$$

where α_A denotes the angle between X_A and X_{Ao} axes.

Figures 7 and 8 show the block diagrams of control systems for the follower and leader robots respectively. In the latter, the controller is made of two sub-components, namely the obstacle avoidance controller and the trajectory following controller. At any given time, only one of these two sub-controllers will be active; it will switch between sub-controllers depending on the situation. On the other hand, the follower robot's controller is composed of an obstacle avoidance sub-controller and a hand-length controller.

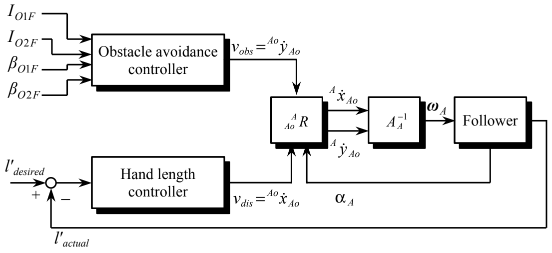


Fig. 7. Follower robot controller module.

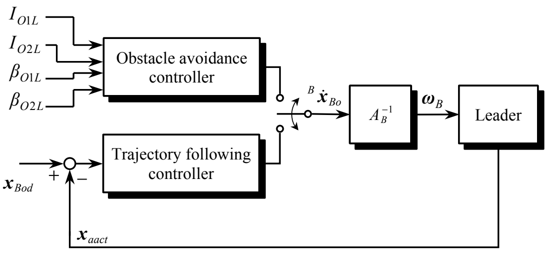


Fig. 8. Leader robot controller module.

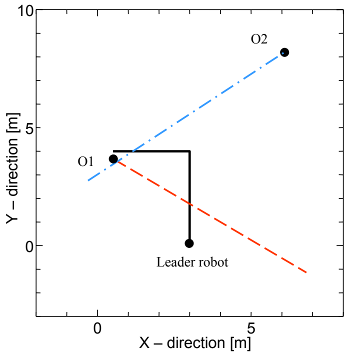


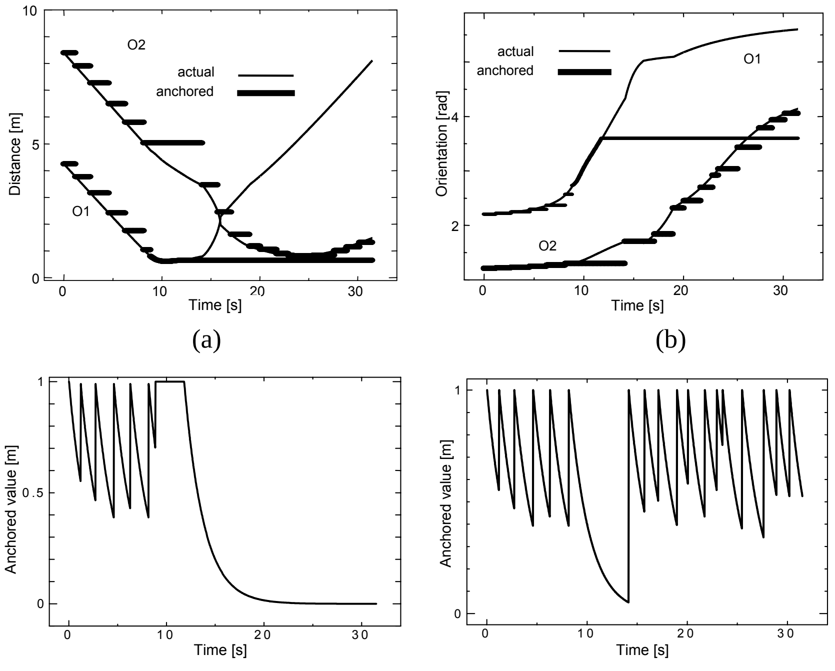
Fig. 9. Desired trajectory for the leader robot and the trajectories for the two other robots working in the environment. Starting positions are marked with a circle.

V. SIMULATION STUDY

We conducted a simulation test to show how the proposed concept works. We used a small size version of the cooperative platform we have shown in the previous section. The wheel radius is set to 0.065 [m]; the offset distance of the reference point from the wheel axis, s, is set to 0.08 [m]; h is 0.06 [m]; the sampling width is set to 0.02 [s]; and the linear velocity of each cooperative robot is limited up to 0.2 [m/s], while the maximum panning velocity for the camera is set to 1.2 [rad/s]. Moreover, aside from the two cooperative robots there are two other robots namely O1 and O2 operating in the same environment. O1 and O2 move along their own trajectories (as shown in Fig. 9) at a speed of 0.15 [m/s].

Other details such as the field of view of the panned camera, ρ, is set to 15 [degrees], the range R is set to 10 [m]; this is enough to exclude the range as a problem source. With this, the problem is reduced to a limited field of view and occlusion. The initial length (or desired length) of the follower's hand and the leader's hand is set to $2s$ [m]. We assume a cargo having a square base with size $2s$ [m] × $2s$ [m].

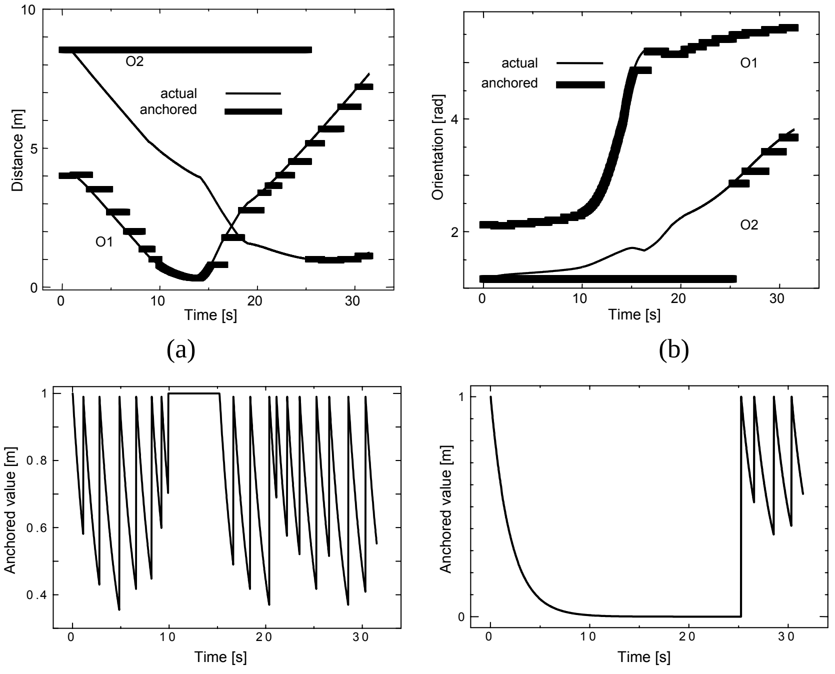
The main task of the two cooperative robots is for them to carry and transport the cargo to the desired location via a predefined trajectory. The trajectories for the leader and the two other robots are shown in Fig. 9. The leader robot task is to follow the trajectory and avoid colliding its body with others. It is assumed here that the two other robots are blind such that



(a) (b)

(c) (d)

Fig. 10. The leader's eye-view. A and B show the anchored and actual values of distance and orientation. C and D on the other hand show the plot of the anchored measure for O1 and O2 respectively.



(a) (b)

(c) (d)

Fig. 11. The follower's eye-view. A and B show the anchored and actual values of distance and orientation. C and D on the other hand show the plot of the anchored measure for O1 and O2 respectively.

they don't have any ability to avoid collision, i.e., they will just go straight and follow their trajectories. On the other hand, the follower robot is designed to have the ability for self and cargo preservation, i.e., it is capable of performing collision avoidance not just for its own body but also for the cargo as well. Moreover, the follower robot is designed to cooperatively carry the cargo safely by maintaining a safe length of its hand. Unlike with the leader robot's hand, the hand of the follower robot are capable of increasing and decreasing its length.

VI. RESULTS AND DISCUSSIONS

The simulation results can be shown in two views, with respect to the leader robot's eye-view and the follower robot's eye-view. For the leader robot's eye-view, the results are shown in Fig. 10, where (a) and (b) show the anchored relative distance and orientation for O1 and O2. On the other hand, (c) and (d) show the anchored (or measure) values for robots O1 and O2 respectively for the entire simulation time. The results show that before hitting the 9 seconds mark, the perception system evenly anchored both O1 and O2. The camera swings back and forth from O1 to O2. Soon, after O1 became so close the avoidance module of the leader robot was activated. The activation resulted in the assignment of higher $needed$ value for the anchor O1. This in turn resulted in a full tracking attention for O1; its anchor contents were updated every sampling time and O2 was left unattended for approximately 3 seconds. When the leader robot and O1 parted ways, O1 swings to the south of the leader robot that later resulted in an occluded view due to the presence of the cargo and the follower robot in that direction. The anchor for O2 was updated again after the close encounter with O1.

For the follower robot's eye-view, the results are shown in Fig. 11, where (a) and (b) show the content of the anchors for O1 and O2 respectively for the entire simulation time, and (c) and (d) show the $anchored$ values for O1 and O2 respectively. The result tells us a different story with what the leader robot saw. The plots show that, for almost the entire simulation time O2 is not visible for the follower robot. It starts appearing only near the end of the simulation time. This is what happens because O2 started up from north relative to the place where the follower robot started (see Fig. 9) and becase it follows the leader robot, it cannot see up north due to occlusion with the leader robot. On the other hand, O1 is visible for all throughout the simulation time.

Here, the two cooperative robots can broadcast to each other their position and the anchors. Specifically, if every time O1 or O2 is lost (or occluded), a cooperative robot will use the information available from the anchor of the other cooperative robot. This technique could result in a more efficient perception control.

VII. CONCLUSIONS

In this paper, we have presented a formalizing approach of controlling the perceptual effort to enhance the awareness of two decentralized mobile robots designed for cooperative transportation of a cargo object, where the two cooperative mobile robots were equipped with panned camera that had highly limited field of view and thus each of the cooperative agent could only focus a small fraction of their environment at any given time. In general, this inherent limitation is further aggravated by occlussion, each cooperative agent can't see through the cargo and its partner. These problems can severely affect the awareness of each agent and will make the task practically difficult to implement. For each cooperative agent to be aware of the state of its environment, each agent must be able to efficiently control its perceptual effort. Our approach to awareness was based on active perceptual anchoring (APA). Through APA each cooperative agent was able to control its perceptual effort according to the needs of the task at hand. We defined awareness as knowing the position of the other robots in the environment and implemented it through the use of anchors. We demonstrated the approach through a simulation of two cooperative mobile robots that cooperatively transport a cargo to a certain destination through a predefined trajectory, in which the two mobile robots cooperatively carrying the cargo, move along a trajectory, and avoid colliding with other robots while moving towards the target distination. Our simulation results showed that our approach could work and was potentially feasible.

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