A PERCEPTIVE REFERENCE FRAME FOR COOPERATIVE AND RECONFIGURABLE MULTI-ROBOT SYSTEMS

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Abstract: This paper presents an analysis and design method for human/robot integrated systems, especially for the cooperative sensing and operation of human and robot formations in human centered environments. The key for the human/robot formation integrated system is to create a common motion reference that can be understood by both human and the robots in the formation. The perceptive reference frame is introduced and the characteristics of perceptive frame are compared with time based reference frame. The applications of perceptive reference frame to multi-agents coordination in a human/mobile manipulators coordination are then discussed. Simulations and experiments have been used to verify the theoretical results. *Copyright © 2005 IFAC*

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1. INTRODUCTION

Mobile robots, each equipped with a variety of sensors, can collaboratively work with human to environmental sensing and detection. For example, figure 1(a) shows a formation composed of a group of mobile robots for cooperative sensing. For certain tasks such as rescue and surveillance, the formation will rely on human intelligence for localization, high level motion planning and decision making. The role of the human is to use his/her perception capability to make decisions and give commands to the mobile robot formation. On the other hand, research interests in coordination of multiple mobile robots for object handing and human/mobile robot cooperation (Fernandez *et al.*, 2001), (Khatib *et al.*, 1999), (Kosuge *et al.*, 2000) have been growing. Multiple mobile robot can work together to handle heavy and oversized objects in large workspace. Figure 1(b) shows a situation where the human and a mobile manipulator work together to handle objects. In the figure 1(c), human is actually freed from tedious task and provide only intelligence and guidance. The mobile manipulators will be assigned to perform the task through interaction. In spite of the various scenarios, the common difficulty for the design of cooperative sensing and operation systems is how to create a motion reference to coordinate the motion of the robots and human. External force can be used for scenarios shown in Figure 1(b) and 1(c), while the motion of the human can be used for cooperative sensing in Figure 1(a). To meet the various application requirements and overcome the difficulties, a perceptive reference frame based approach is introduced to

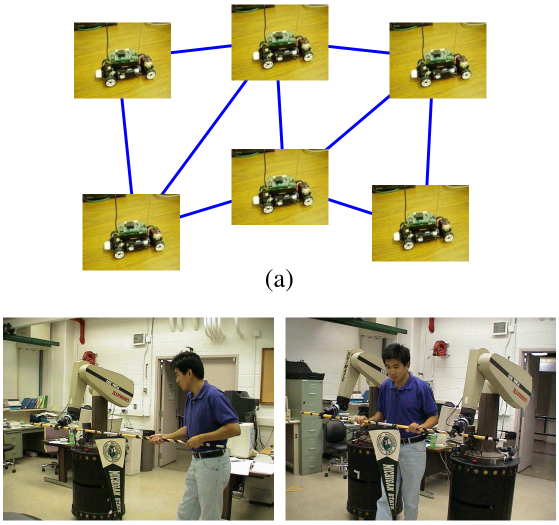


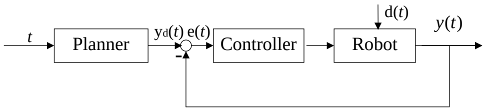
Fig. 1. (a) Cooperative sensing by a mobile robot formation; and (b) (c) cooperative operation by mobile robots and human

ease the integration of human intelligence and robot capabilities.

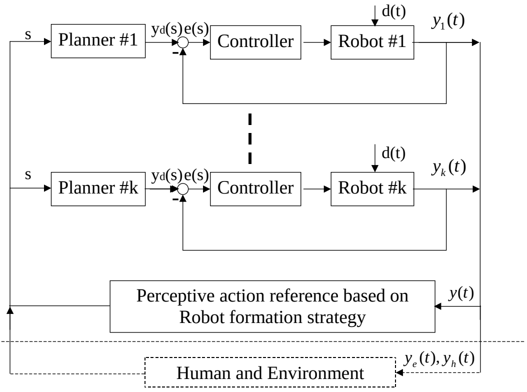
2. PERCEPTIVE REFERENCE FRAME

The basic idea of perceptive planning and control theory (Xi *et al.*, 1996) is to introduce the concept of a perceptive action reference, a parameter that is directly relevant to the measured sensory outputs and the task. Instead of time, the control input is parameterized by the perceptive action reference. Since the action reference is a function of the real time measurement, the values of the desired vehicle states are functions of the measured data. This creates a mechanism to adjust or modify the plan based on the measurements. Thus, the planning becomes a closed loop real-time process. The planner generates the desired values of the system, according to the on-line computed action reference parameter s. This perception based planning and control scheme has been successfully applied to deal with unexpected obstacles during robot motion and multi-robot coordination (Xi *et al.*, 1996).

When multiple robots in a formation are involved in the same mission, perceptive reference projection can be used for cooperated motion control of the multiple vehicles. To extend the perceptive planning and control theory to the formation control composed of heterogeneous robots, the perceptive motion reference has to be chosen such that all the information of the robots in the formation are properly represented. As shown in Figure 2(b), the perceptive reference not only considers the system output of one robot, but also the mission of the formation described by the system output of all the robots in the formation. The motion of the robot in this formation is coordinated by the common motion reference, s, which is related to the system output of the robots. Since the task planner is driven by s, instead of time, the behavior of one robot in the formation will affect the mission of the formation by affecting the motion reference s. For example, if the motion of one robot is stopped by an unexpected event, such as an obstacle in unstructured environments, this event will affect the computation of s according to the specification of the coordination scheme.



(a) Time based system



(b) Perceptive reference based system

Fig. 2. Perceptive planning and control for robot formations

Another advantage of the perceptive planning and control scheme lies in the ease of integrating human intervention in the formation. Since the behavior of the formation is coordinated by the common motion reference, the intention of human or the human's command can be modified by the varying of the motion reference to achieve the goal of the human and adjust the mission and/or behavior of the formation, as is shown in Figure 2(b).

The system stability under the perceptive reference frame has been investigated. Under the assumption that the action reference s is nondecreasing with respect to time t, it can be proved that the system in perceptive reference frame is stable provided that the system is asymptotically stable in time domain (Kang *et al.*, 2001), (Kang *et al.*, 1999). However, the restriction on the definition of the motion reference restricts the application of the perceptive reference frame. It is seen in Figure 1, the motion reference could be the trajectory of the one robot in Figure 1(a), the position estimation of human in Figure 1 (b), or the external force felt by the mobile manipulators in Figure 1(c) and (d). The system in perceptive frame is still stable even when a decreasing force, for instance, is adopted as the motion reference.

In this paper, the definition of perceptive reference frame is modified to incorporate these challenges. The system stability should be ensured based on the perceptive motion controller design method and the stability analysis of the system.

2.1 Perceptive Controller Design.

The model of the mobile robots in a formation and their output can be described as:

$$\begin{array}{l} \dot{x}_i = f_i(x_i, u_i) \\ y_i = h_i(x_i) \\ i = 1, \cdots, k \end{array} \tag{1}$$

where k is the total number of robots in a formation, x_i is the state variable of the ith robot, y_i is the output of ith robot and u_i is the control input vector of the ith robot. h_i represents the robot output function. For a formation with a variety of robots, the kinematic function f_i may be different. For each robot, a path tracking controller in time domain can be designed and a path tracking controller in perceptive reference frame can be obtained according to the following steps.

The first step is to find a suitable transformation from the state space, environments and human intention to the reference s. Here s can be a function of the internal state output of the system, such as system output y_i. It could also be mapped from the sensory information from the formation and/or the environment, such as vision, external force, human intention, etc. For a human/mobile manipulator coordinated system, the estimation of the human's intention could be used to map as the motion reference. It could also be used to modify the motion reference. In brief, the motion reference could be described as $s = \gamma(y_i, y_e, y_h)$ where $y_i, i = 1, \cdots, k$ is the output of the formation, y_e is the estimation of the environments, and y_h is the intention of the human.

The second step in the controller design is to generate a corresponding path in the perceptive reference frame. Given a mission of the formation, the desired motion of each robot in the formation $y_i^d(s)$ may be different. Here s is a unified perceptive motion reference. How to pick up the motion reference depends on the desired motion of the formation. Notice that the desired trajectory of the formation is defined as a function of s, $y^d(s)$, as shown in Figure 2(b), not by a trajectory in time domain $y^d(t)$, as shown in Figure 2(a). Here is s the perceptive motion reference, the relation between s and time t can be defined as $s = v(t)$. Based on the perceptive motion reference, a formation control law is a feedback $u = \alpha(x)$ such that

$$\lim_{t \to \infty} (y_i(t) - y_i^d(s)) = 0.$$

The third step is to find a feedback law, $u_i = \alpha_i(x)$ to track the path $y_i^d(v(t)) = y_i^d(s)$, where $s = v(t)$ is the relation between the time and perceptive action reference. There exist many well-known design algorithms in the literature of control theory. The feedback satisfies

$$\lim_{t \to \infty} (h_i(x_i(t)) - y_i^d(s)) = 0.$$

Furthermore, if the initial condition is on the desired path, then the trajectory of the controlled system follows the path. More specifically, there exists an initial condition of the system x_0 such that $h_i(x(t)) = y_i^d(s)$. It worth noting that the perceptive reference s is a motion reference projection that affects the control, but not part of the control. The closed-loop system is

$$\dot{x}_i = f_i(x, \alpha_i(x)). \tag{2}$$

2.2 Stability Analysis

There are generally two ways of designing a non-time based tracking systems. One way is to express the original dynamic system based on the pre-defined non-time based scale and then design the feedback controller for the non-time based system (Hollerbach, 1984), (Sampei and Furuata, 1986). A more recently developed approach is to design the feedback controller in time domain based on the well known system design approach. A motion reference projection method can then be used to project the time based controller to a non-time based controller. The system stability has been proved under certain necessary conditions (Kang *et al.*, 2001), (Kang *et al.*, 1999), (Xi *et al.*, 1996). The perceptive motion reference is required to be nondecreasing with respect to time. This restricts the applications of perceptive motion reference frame. Based on the perceptive controller design procedure discussed above, the restriction can be released and the following theorem can guarantee the system stability in the perceptive reference frame.

Theorem 2.1. Suppose system $\dot{x} = f(x, \alpha(x))$ in time domain is uniformly asymptotically stable in $||e|| < \delta$. Assume the system has solution for $t > 0$ and $[\partial f / \partial x]$ is bounded on D, uniformly in t. Assume the controller in time domain $u = \alpha(x)$ can tract a variety of trajectories $g_t(t)$ as long as $g_t(t)$ is globally Lipschitz and piecewise continuously differentiable, then the controller in perceptive reference frame is asymptotically stable.

proof. Comparing the two systems in Figure 2, the error function could be different under two reference frames. In time domain, as shown in

Figure 2(a), the reference trajectory can be given as:

$$y_t^d = g_t(t).$$

To satisfy the velocity and acceleration constraints of the robot system, it is reasonable to assume that the function $g_t(t)$ is globally Lipschitz. The error function in time domain, $e = y(t) - g_t(t)$ is also globally Lipschitz. The trajectory in time domain can further be assumed piecewise continuously differentiable for certain trajectory planning approaches.

The reference trajectory in the perceptive reference frame, as shown in Figure 2(b), can be described as

$$y_s^d = g_s(s),$$

where s is the perceptive motion reference. The trajectory in perceptive reference frame can also be assumed Lipschitz and continuously differentiable with respect to the perceptive motion reference s. In spite of the definition of the motion reference $s = \gamma(\cdot)$, s can be assumed continuous and the relation to time can be described as $s = v(t)$. The error function in perceptive frame is therefore defined as $e_s = y - g_s(s)$.

In time reference frame, the robot controllers can be designed such that the robot can track any two trajectories: $y^d = g_t(t)$ and $y'^d = g'_t(v(t)) = g'_t(s) = g_s(s)$, as long as $g_t(t)$ and $g'_t(v(t))$ satisfy the constraints above mentioned. The error functions in time domain can be defined as $e = y(t) - g_t(t)$ and $e' = y'(t) - g'_t(v(t))$. From the converse Lyapunov theorem for stability, there exists a Lyapunov function $V(e)$ for both trajectories that satisfy

$$\begin{aligned} &\alpha_1 ||e||^2 \le V(e) \le \alpha_2 ||e||^2, && t \ge t_0 \ge 0, \\ &\frac{\partial V(e)}{\partial e}\dot{e} \le -\alpha_3 ||e||^2, && t \ge t_0 \ge 0, \\ &\left|\left|\frac{\partial V(e)}{\partial e}\right|\right| \le \alpha_4 ||e||, && t \ge t_0 \ge 0, \end{aligned} \tag{3}$$

in a neighborhood $|e| < \delta$. Both e and e' satisfy the inequalities in eq. (3).

To evaluate the system stability in perceptive reference frame, the error functions in time reference frame and perceptive reference frame have to be related. There are two situations. In an autonomous system, the desired geometric trajectory is generally predefined. The environment and/or human would not alter the predefined path. The map of motion reference can be defined as $s = \gamma(x)$, where x is the system state variable. As discussed in (Kang *et al.*, 1999) and (Kang *et al.*, 2001), the unexpected event cannot affect the system stability under the perceptive reference frame. The error functions in two frames can be related and the system stability in perceptive frame is proved.

However, in a system composed of multiple mobile manipulators and human, there is generally no predefined path. The path is determined by human's intention, and can be altered when unexpected events occur. The perceptive motion reference is defined as $s = \gamma(y, y_h, y_e)$, which is continuous with respect to time. It is reasonable to assume that perceptive motion reference s is globally Lipschtiz with respect to time. For this situation, it is difficult to directly relate the error function in two reference frames. However, since the system dynamics in the inner loop of Figure 2(b) remain unchanged, the error function e_s in perceptive reference frame is defined as $e_s = y' - g_s(s) = e'$. Since e' satisfies eq.(3), a Lyapunov function function $V(e_s)$ in the perceptive frame can be found such that

$$\begin{aligned} &\alpha_1 ||e_s||^2 \le V(e_s) \le \alpha_2 ||e_s||^2, && t \ge t_0 \ge 0, \\ &\frac{\partial V(e_s)}{\partial e_s}\dot{e}_s \le -\alpha_3 ||e_s||^2, && t \ge t_0 \ge 0, \\ &\left|\left|\frac{\partial V(e_s)}{\partial e_s}\right|\right| \le \alpha_4 ||e_s||, && t \ge t_0 \ge 0. \end{aligned} \tag{4}$$

Therefore,

$$\dot{V}(e_s) = \frac{\partial V(e_s)}{\partial e_s}\frac{\partial e_s}{\partial s}\dot{s} = -\alpha_3 ||e_s||^2, \; t \ge t_0 \ge 0. \tag{5}$$

Therefore, the system under perceptive reference frame is asymptotically stable according to the Lyapunov stability theorem.

The physical meaning of the theorem can also be explained. Before the operation of a robot task, the perceptive reference is "virtual" since it depends on the evolution of the system, such as the output y, and some unexpected events. Therefore the actually value of the desired path is unknown. However, the desired trajectory of the system in perceptive frame is determined by the perceptive motion reference, which could be altered during the process. It will be be related to time after s becomes "real". In the other words, when s is determined by the occurrence of all the unexpected events. If the system is stable while tracking the resultant trajectory in time domain, it is stable in the perceptive frame. It is worthy noting that the relationship between motion reference and time, $s = v(t)$, does not have to be an explicit function at the time of the system design. The controller uses only the system output or state variables, therefore the controller is only indirectly related to time t by the evolving of the state variables and/or the system outputs. $\triangleleft$

3. HUMAN/MOBILE ROBOT COOPERATION

Cooperative Sensing. The mobile robots form a communication network for collaborative sensing. If one robot forms a motion plan based on the interaction with human, network flooding protocol can be used to send the formation plan in terms of motion reference to all the other robots in the network. It is worthy noting that the interpretation of the same plan in each sensor node is different from each other. Denoting s as the desired path of the formation and s_i is its interpretation in the coordinate system of robot R_i, the information sharing between neighboring robots R_i and R_j is done by a transformation matrix. The perceptive motion reference for coordinated formation control has the freedom to be determined according to the coordination strategy. For an autonomous mobile manipulator formation, the reference could be chosen differently to implement different coordination strategies.

Cooperative Operation. In this application of perceptive reference, two situations are discussed: One mobile manipulator and a human handling an object, as shown in Figure 1(b); and two mobile manipulators and a human handling an object, as shown in Figure 1(c). When a human transports an object cooperating with another human, humans unconsciously communicate with each other through the interacting force while sharing the load of the object. The intention of human is actually transported by force. For the object handing by a human and a mobile manipulator, as shown in Figure 1(b), the desired trajectory in a perceptive frame should be given based on a reference that reflects the intention of human and actual motion of the mobile manipulator. For example, the perceptive motion reference can be defined as:

$$s = k * f_h, \tag{6}$$

where k is a constant scalar, f_h represents the estimation of the force felt by the robot. In eq.(6), the reference is defined solely depending on the force. However, the perceptive reference can also be defined based on both internal state x and human intention f_h, *i.e.,* $s = \gamma(f_h, x)$. The trajectory in perceptive frame can be defined as a function of s. In the two mobile manipulators case, the force f_h is composed of force felt by the mobile manipulators. It has to be computed to define the perceptive motion reference. The two mobile manipulators actually cooperate based on the common motion reference.

4. EXPERIMENT SETUP AND RESULTS

The perceptive reference frame approach and its applications in the coordination of human and mobile manipulators have been tested on a mobile manipulator consisting of a Nomadic XR4000 mobile robot and a Puma560 robot arm. The end-effector is equipped with a Jr3 force/torque sensor to interact with human. Simulations have been conducted for the cooperative sensing of robot formations.

Robot Formation for Cooperative Sensing. Figure 3 shows the simulation results of the algorithms. The desired motion of the formation s is a sinusoidal wave, assuming the human motion is zigzag. This information is sent to the leading robot and then flooded to the robot formation. The leading robot keeps on sending out its desired motion to the system. From the simulation results, it can be seen that the formation follows the desired path of the formation, which is a sinusoidal wave. The synchronous formation control is not a leading-follower system. If the leading robot fails during the operation, any other robot can act as the leading robot instead.

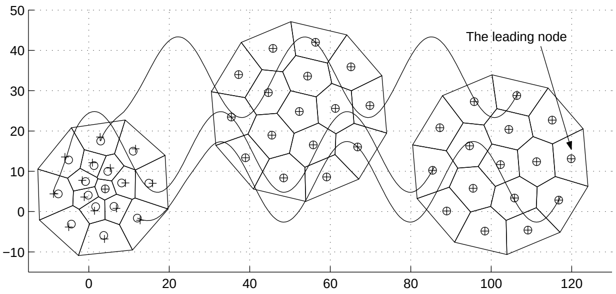


Fig. 3. The formation follows a sinusoidal wave and maximize its coverage area during the operation.

Robot Formation for Cooperative Operation. The experiment result for the scenario in Figure 1(b) is shown in Figure 5. In this experiment, human holds one end of a rod and the mobile manipulator holds the other end. Human and mobile manipulator cooperate to perform certain task. The motion reference s is the force felt by the end effector of the mobile manipulator. The desired trajectory of the mobile manipulator is selected as $y^d(s) = k_f \int_o^t s(\sigma)\mathrm{d}\sigma$, where k_f is experimentally determined constant. This constant determines the "sensitivity" of the robot while interacting with human being.

Figure 4 and 5 show the experimental result while human working with a formation of mobile manipulators. In this scenario, the two mobile manipulators hold two ends of a rod and the human leads the motion of the rod by the interaction force. The mobile manipulators are designed to follow the force felt by their end effectors. Figure 4 (a) and (b) show the trajectory of the mobile manipulator R_1 in x and y directions respectively. The force along x and y directions are shown in Figures 4 (c) and (d) respectively. Figure 5 (a) shows the trajectory of the rod; Figure 5 (c)and(d) show the force along x and y directions with respect to time. Figures 4 (b) is the path of a mobile manipulator with respect to time. It can be seen that the intention of the human is executed by the robot formation. The operation lasts about $8sec$, the speed of the operation can be seen by the comparison of Figures 4 (a) and (b). Human's intention also determines the speed of operation. The compliance of the human robot formation interaction can be regulated by the definition of $y^d(s)$.

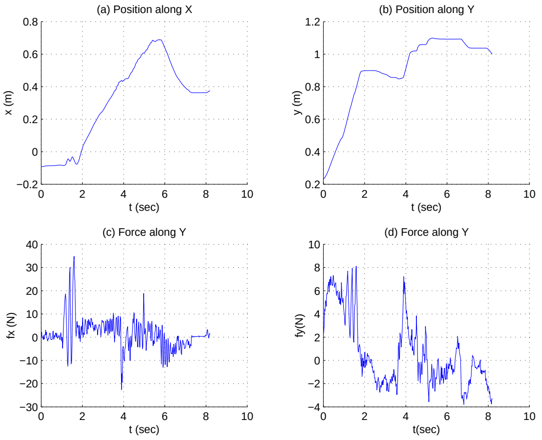


Fig. 4. Cooperation of Human and Multiple Mobile Manipulators, as shown in Figure 1(d)

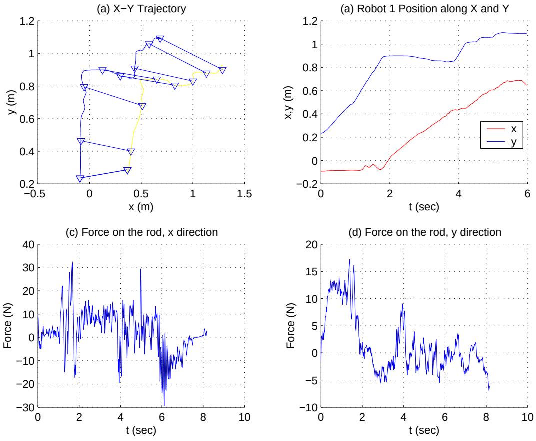


Fig. 5. The Path and Perceptive Motion Reference in the Cooperation of Human and Multiple Mobile Manipulators

5. CONCLUSIONS

Perceptive planning and control theory is devised for human/machine cooperative control of robot formations. This approach replaces the need for replanning and allows for control transition on the fly. In addition, it integrates human intelligence and eases the design of robot controllers for human/robot formation cooperation. This paper gives the procedure for robot controller design in a perceptive frame.

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