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Human-Centered Robot Navigation --- Toward a Harmoniously Coexisting Multi-Human and Multi-Robot Environment

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Abstract—**This paper proposes a navigation algorithm that considers the states of humans and other robots in order to achieve harmonious coexistence between robots and humans. When navigating through humans and robots with different functions, a robot should not only pay attention to obstacle avoidance and goal seeking, it should also take care of whether it interferes with other people or robots. To deal with this problem, we propose several harmonious rules, which guarantee a safe and smooth navigation in multi-human and multi-robot (MHMR) environment. Based on those rules, a practical navigation method–human- centered sensitive navigation (HCSN)–is proposed. HCSN considers the fact that both humans and robots have sensitive zones depending on their security regions or on psychological feeling of people. We model these zones as various sensitive fields with priorities, whereby robots tend to yield socially acceptable movements.**

I. Introduction

NAVIGATION is one of the most fundamental functions of a mobile robot. Since robots are going to live or work with human beings, we as robot theorists should pay more attention to the robot-human interaction when a robot navigates in a multi-human and multi-robot (MHMR) environment. There are two main issues that should be addressed here: (1) the robot can move autonomously and safely in MHMR environment in order to complete a specific task; (2) the robot should behave in a both human-friendly and robot-friendly manner during its movement. In the past research, the second issue has rarely been given a significant consideration. However, that is exactly what this research work mainly wants to investigate in particular. In fact, our work is based on the belief that there should be plausible rules between robots and humans to maintain safe and smooth navigations for all of them just like that there are traffic rules currently to maintain the safety both drivers and pedestrians.

Human-robot interaction in the tasks of mobile robot navigation task has been addressed by several researchers. Alami *et al.* proposed an idea of designing a human-friendly navigation system [1]. Althaus *et al.* developed a method for the robot to join a group of people engaged in a conversation in a friendly manner [2]. A human aware mobile robot motion planner, proposed by Sisbot *et al.* [3], defines a scenario of how robot approaches a human. They consider the non-written rules of human-robot or human-human interactions and integrate those rules into path planning. Topp *et al.* used SJPDAFs to track people in order to let a robot follow a specific person [4]. In [5], the authors observe the moving patterns and trajectories of people in house and then apply these patterns to improve the mobile robot navigation in the house. In [6], the author estimates the human pose and uses "Person Interest" indicator to generate an artificial potential field, resulting to a human-aware navigation. However, these researches mentioned above all failed to consider the disturbance to humans and other robots when the host robot is moving through them and how the host robot can achieve a socially acceptable navigation.

In this paper, we propose six harmonious rules that a single robot should obey in order to achieve not only a safe but also a least disturbance motion in MHMR environment. Moreover, based on those rules, a practical navigation algorithm, named human-centered sensitive navigation (HCSN), are proposed. Such algorithm not only provides a collision-free navigation in MHMR environment, but also imposes the least disturbance to dynamic people and robots.

This paper is organized as follows: first, we provide the main characteristics of the harmonious rules in section II. In section III, we describe how we model the sensitive zones of humans and robots. The details of HCSN will be demonstrated in section IV. Simulations and experimental results are presented in section V and VI. Finally, we draw a conclusion and future work in section VII.

II. Six Harmonious rules

Various rules have existed in human society for long time. Among vehicles, traffic rules regulate their behaviors like limiting their velocities, restricting the driving directions or deciding priorities over different vehicles, etc. Therefore, some rules must be applied to the robots to regulate their behaviors similarly. Those rules should consider two major issues, namely, safety and smoothness. Safety ensures collision-free robot navigating in MHMR environment, whereas smoothness enables robots not to interfere with humans and one another. The rules are:

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1) ***Collision Free Rule:*** The host robot has to maintain its safety and be able to reach the goal destination.
2) ***Interference Free Rule:*** The host robot should not enter the personal space of a human and the working space of any other robot unless its task is to approach any of them.
3) ***Waiting Rule:*** Once the host robot enters the personal space of a human carelessly or unwillingly, it has to stop and to wait for a threshold time.
4) ***Priority Rule:*** The host robot with low priority should yield to the robot with higher priority when two are both moving.
5) ***Intrusion Rule:*** The host robot intruding other robots' working spaces should leave immediately. The robot whose working space has been intruded should stop working for safety concern.
6) ***Human Rule:*** Human has the highest priority. Once a robot is serving humans, it only needs to maintain the "Collision Free Rule" and "Interference Free Rule".

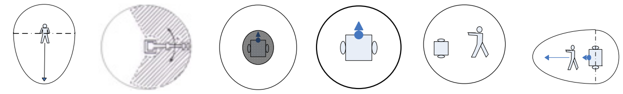
In addition to the six harmonious rules, robots of the same type may have their internal rules in order to carry out some special mission. However, the rules above are the most basic rules to ensure harmony.

III. Various Sensitive Fields

We consider the fact that both humans and robots have their sensitive zones depending either on their security regions or on psychological feeling of humans, and we then model these zones as various sensitive fields with priorities. Those fields will provide criteria to our human-centered sensitive navigation.

1) H1: Human Sensitive Field

The research by Hall [7] proposed social spaces of associated humans A robot entering the human's personal spatial zone will make that human uncomfortable, just like the situation where a stranger enters one's personal spatial zone. Sisbot *et al.* [9] used cost functions to model the personal spatial zones of stationary people. However, for a moving person, we would like to take more consideration on the influence of his/her velocity upon his/her personal spatial zone rather than only on that of his/her gaze direction. In order to handle this problem, we model the personal spatial zone of a human as a human-sensitive field which is egg-shaped, *i.e.*, the shape of the field is a combination of a semi-ellipse and a semi-circle. As shown in Fig.1(a), the semi-ellipse models the human-sensitive field in front of a person and the semi-circle models the field behind the person. A philosophic reason behind this is that a human while walking ahead may prefer to have longer clear space along his/her way of heading but can accept that an unexpected pop-up robot may get closer to him/her if its approaching direction is within the field of view of the person. Conceivably, the field H1 should have the highest priority among all the sensitive fields because it involves humans.



(a) (b) (c) (d) (e) (f)

Fig.1 Six kinds of sensitive fields: (a) H1. (b) R1. (c) R2. (d) R3. (e) HR1. (f) HR2

2) R1: Stationary Robot Working Field

This field models the sensitive field of a stationary robot. It appears in two kinds of situation. The first situation is when the robot is not equipped with mobility but works only at a fixed location, like a manipulator. The second situation is where the robot though being able to move needs to stay at a fixed place when it is working. This sensitive field, as shown in Fig.1(b), is modeled as a round disc, whose radius depends on the working space of the robot. Here, the priority of this sensitive field, R1, is set to be the 2nd.

3) R2: Movable Robot Working Field

Some robots can move even though they are working, like robotic vacuum cleaners. Since they are able to choose where to go, their working spaces are moving as well. In this case, the movable robot working field is modeled as a two-layer field, where the inner layer models its current working space, and the outer layer models its possible working space within a short-term future. The shape of such sensitive field is like a donut, and its priority is set to be the 3rd.

4) R3: Robot Normal Field

In the case the robot is either being idle or waiting for human's order. Such field has the lowest priority, the 4th rank, among all sensitive fields. This field is also modeled as a round disc with a predefined radius.

5) HR1: Human-Robot Stationary Joint Field

In some situations, the robot is serving a human at a fixed location. As shown in Fig.1(e), the human being served and the serving robot together form a joint field with a disc shape, named human-robot stationary joint field. Since human being is involved in the field HR1, its priority is the same as that of H1.

6) HR2: Human-Robot Moving Joint Field

This situation happens when the robot is following a human or, on the contrary, when the robot is leading a human. The shape of this field, called human-robot moving joint field, is the same as that of H1, an egg-shape. With similar reason, the field HR2 as shown in Fig.1(f) has the highest priority as well.

We believe that the six sensitive fields presented above cover most of the general situations that a single robot will face. For multiple robots working on a single task, we can simply regard them as a single robot situated at the center of the multi-robot system and then fit it with one of the six sensitive fields.

Besides, we divide the 6 fields into two different groups: one with solid fields and another with soft fields. The field belonging to the first group is regarded as an obstacle that any other robot cannot intrude, and H1, R1, HR1, HR2 and the

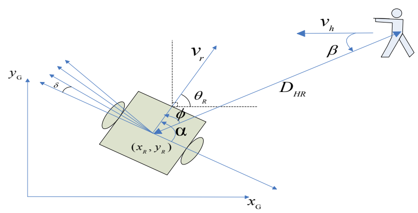


Fig. 2 Robot coordination

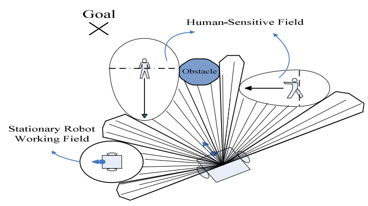


Fig. 3 Human-Sensitive Field

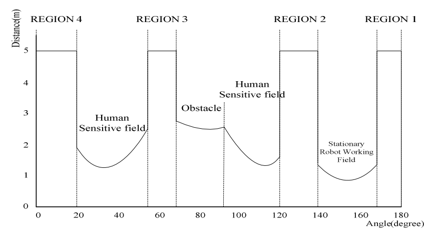


Fig. 4 Virtual Laser Histogram

inner layer of R2 all belong to this group. Intrusion into any solid field is not allowed because it violates the "Interference Free Rule" or "Intrusion Rule". Soft field belonging to the 2nd group is regarded as a flexible ball with different elasticity, and R3 as well as the outer layer of R2 are exactly members of this group of field.

IV. Human-Centered Sensitive Navigation

A. Architecture

Based on the 6 harmonious rules, we design a navigation algorithm, named human-centered sensitive navigation (HCSN). As shown in Fig.5, human sensitive navigation includes sensitive field sensing, self-situation identification, a motion planner, and a controller.

The state of a human is defined as $\mathbf{s}_h = [x_h, y_h, \theta_h, v_h]$, including his/her position, heading angle, and velocity, which are the outputs of the human tracking system. Unlike human state, we can get much more information about a robot. Here,

$$\mathbf{s}_r = [ID_r, x_r, y_r, \theta_r, v_r, m_r, R_r, R_r^{inn}, \mathbf{H}, B_r]$$

is defined as the state of a robot, and we assume that all the robots have the ability to constantly broadcast their states by applying the existing techniques like WiFi or Zigbee. Specifically, ID_r is a robot's identification, and every single robot should have a unique identification just like the MAC address in a computer network. The data vector $[x_r, y_r, \theta_r, v_r]$ is used to describe robot's posture and velocity; notation $m_r \in \{R1, R2, R3, HR1, HR2\}$ describes the sensitive field the robot deserves; notation R_r is the radius of the sensitive field; notation R_r^{inn}, used only when the robot is with R2 field, denotes the radius of the inner layer of R2; notation $\mathbf{H}$, used only when the robot is with either HR1 or HR2 field, denotes the state of human(s) whom the robot is serving; $B_{r_r} = [MoveAway\_ID]$ is a communication signal among robots, and this signal is sent to the robot with "*MoveAway_ID*" if it enters the solid field of the host robot.

B. Sensitive Field Sensing

In this work, we assume that the robot can gather the state of people near itself by an appropriate human tracking system, and simultaneously nearby robots can communicate with one another by broadcasting through wireless network so that a robot will be able to know the states of other nearby robots. As a result, humans and robots can be divided into six groups, $S_{H1}, S_{R1}, S_{R2}, S_{R3}, S_{HR1}$ and S_{HR2} according to their states.

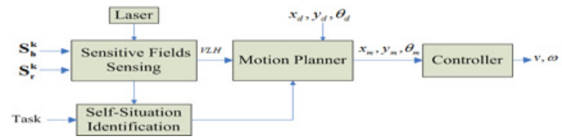


Fig.5 Human-Centered Sensitive Navigation (HCSN) design

So far from what we have described, overall there are two kinds of fields, solid field and soft field. The soft field of robot *j* affects robot *i* if

$$\sqrt{(x_{r_i}-x_{r_j})^2+(y_{r_i}-y_{r_j})^2} < R_{r_j}, \quad r_j \in S_{R2}\cup S_{R3} \qquad (1)$$

On the other hand, since solid fields are regarded as a solid obstacle, any robot should be able to "see" those surrounding it through sensing with laser rangefinders. We set the length of the semi-major axis a_{obj_k} by eq. (2), which is proportional to the velocity of the person in H1 or HR2:

$$a_{obj_k} = b_{obj_k} + \lambda v_{obj_k} \text{ for } obj_k \in S_{H1}\cup S_{HR2} \qquad (2)$$

where v_{obj_k} is the velocity of object k and λ is a scalar. The length of the semi-minor axis b_{obj_k}, the same as the radius of the semi-circle, is used to model the general safety zone of a person. As we mentioned before, b_{obj_k} can be a function of physical states, such as age or posture, of a human. For the circle shaped solid field, we set lengths of major and minor axes as :

$$\begin{aligned} a_{obj_k} &= b_{obj_k} = R_{obj_k} \text{ for } obj_k \in S_{R1}\cup S_{HR1} \\ a_{obj_k} &= b_{obj_k} = R_{obj_k}^{inn} \text{ for } obj_k \in S_{R2} \end{aligned} \qquad (3)$$

We can calculate the virtual distance by simply solving the equation of the semi- ellipses, semi-circles and straight line (laser beam).

By collecting all the virtual distance data, we create a virtual laser histogram (VLH), as shown in Fig. 4. It is noteworthy that this VLH has taken into consideration the sensitive fields of all the observed people.

C. Self-Situation Identification

The term "self-situation" refers to the state of a robot relative to the six kinds of sensitive fields that the robot itself is currently involved in. A robot should always maintain its self-situation in order to provide correct information to other robots and its own motion planner that determines how the robot should move while reacting to the other fields currently under interaction. Figure 6 shows the example of the finite state machine of the self-situation identification block.

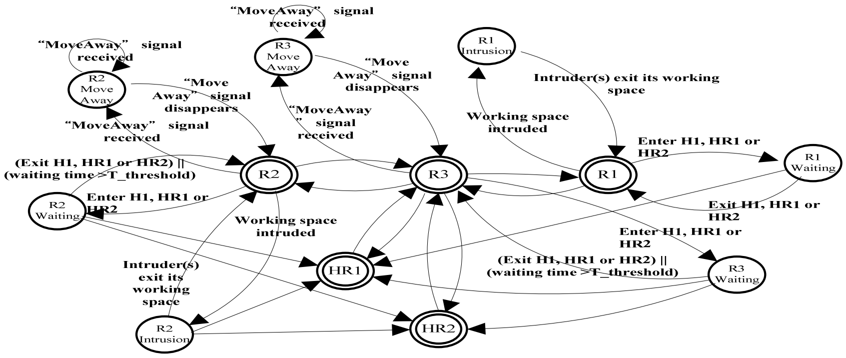


Fig.6 Example of finite state machine for "Self-Situation Identification" block

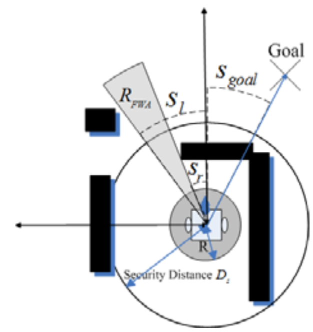


Fig. 7 Example of LS2

A robot entering solid fields will be transitioned into the intermediate state, "Intrusion" or "Waiting". After the robot is transferred from the state "R2" to the state "Intrusion" when some other robot enters its solid field, what it does is to send a "MoveAway" signal to the intruding robot. Only robots with field R2 or R3 state need to react to "MoveAway" signal because of their lower priorities.

The "Waiting" state most likely happens when a human himself or herself approaches the robot so that robot enters the human sensitive field unwillingly. There are three possible reasons why people will approach a robot:

(1) People pass by the robot only: In this case, the robot first stops and later returns to its original state after people leave.

(2) People require some services from the robot: Therefore, the robot waits for human's command and then directly enters "HR1" state or "HR2" state.

(3) People are not aware of the robots nearby: the robot will leave the human sensitive field by itself if the waiting time exceeds a threshold time.

D. Motion Planner

Motion planner aims to provide a sequence of robot motions that are subjected to "Collision Free Rule", "Interference Free Rule", and "Priority Rule", which amounts to provide a solution to the underlying navigation problem. Such planner is based on two reactive navigation methods, namely, ND (Nearness Diagram) navigation [9] and potential field navigation [8]. We use ND to find out a suitable free walking area first. After that, a potential field approach is used to establish different potential fields near the free walking area we choose. Furthermore, we consider the priorities of different sensitive fields when creating potential field function so that a robot with higher priority will tend to go first.

From sensitive field sensing, we have obtained the VLH, which will replace the raw laser data to find out free walking area from nearness diagram. Referring to Fig. 7, let R_{FWA} indicate the free walking area, R is the radius of the robot or the radius of robot's solid field and $d_{\max}$ is the maximum laser distance that we concern. All these notations follow the definitions made in [11]. In that work, ND navigation divides the robot's behaviors into six scenarios namely, HSGR, HSWR, HSNR, LS1, LS2 and LSGR.

After that, a modified direction s_θ for the robot to go along is searched. For scenarios that the robot is in high safety condition, *i.e.*, the robot does not enter any sensitive field and is not close to any obstacle, and hence we just follow the original strategies proposed in [11] to determine s_θ.

In scenarios that the robot is in low safety condition, the original strategies in [11] only take account of the closest obstacle points in both sides. However, the closest obstacle may not be the most dangerous obstacle. As shown in Fig. 7, the closest obstacle is the obstacle at the right hand side of the robot. However, that obstacle nearly does not affect the safety of robot because the robot would not take a lateral movement. When the robot continues to go ahead until the obstacle in front of it becomes the closest obstacle, s_θ will change significantly, resulting in a non-smooth motion. Hence, we have to estimate the risk of each obstacle point. The risk measurement rk_i is hereby defined by

$$rk_i = \left(\frac{PND_i}{d_{\max}+2R}\right)^2 \sqrt{\cos(\theta_{obs(i)})} \tag{4}$$

with $\begin{cases} PND_i = d_{\max} + 2R - D_{VLH}(i) & \text{if } (D_{VLH}(i) < d_{\max}) \\ PND_i = 0 & \text{if } (D_{VLH}(i) \geq d_{\max}) \end{cases}$

where PND stands for ND from the central point [9], and $\theta_{obs(i)} \in [-\pi/2, \pi/2]$ is the angle of the obstacle point from the robot local coordinate. The risk measurement increases the
weight of obstacle point whose direction is close to the facing of the robot.

Furthermore, since "Priority Rule" has to be satisfied, the priority should be introduced when determining s_θ. Potential field method provides a good solution to handle it. We construct the attractive force as follow. The magnitude of the attractive force is:

$$F_{att} = \xi, \quad where\ \xi\ is\ a\ cons\tan t \tag{5}$$

The direction of F_{att} is determined by:

$$\begin{cases} s_{att} = \left[\dfrac{s_r + s_l}{2} + \kappa_\theta (rk_{r,\max} - rk_{l,\max})\right] & \text{if robot is in LS1 or LS2} \\ s_{att} = s_{goal} & \text{if robot is in LSGR} \end{cases}$$

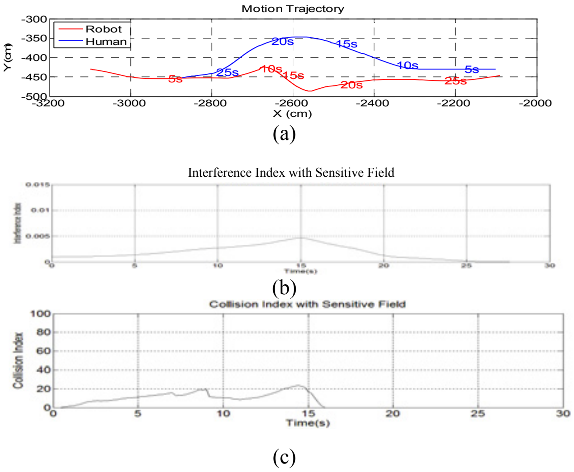


Fig.8 HCSN in the scenario of human and robot moving opposite on a corridor (a) Motion Trajectory (b) Interference Index (c) Collision Index

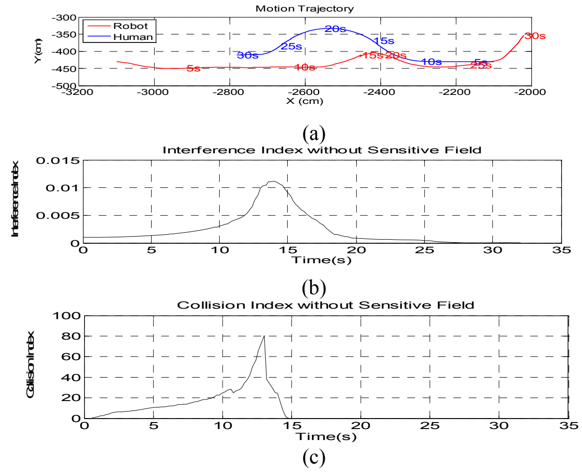


Fig.9 Human and robot move opposite on a corridor without sensitive field (a) Motion trajectory (b) Interference index (c) Collision index

where $rk_{l,\max}$ and $rk_{r,\max}$, the maximum values of the left hand side risk measurement and the right hand side risk measurement, respectively, are used to finely tune the direction of the attractive force; and κ_θ is the positive constant value that can be tuned experimentally.

The corresponding repulsive force is given by:

$$F_{rep}^{VLH}(q) = -\nabla U_{rep}(q) = \begin{cases} \sum \eta_i \left(\frac{1}{\| q_{obs} - q \|} - \frac{1}{D_s}\right) \frac{1}{\| q_{obs} - q \|^2} \nabla(\| q_{obs} - q \|) & \text{if } \| q_{obs} - q \| \le D_s \\ 0 & \text{if } \| q_{obs} - q \| \ge D_s \end{cases} \quad (6)$$

where $q = (x, y)^T$ is the position of the host robot, η is a scalar, and to introduce the priority, the value of η depends on the corresponding VLH, that is, $\eta_{obs} > \eta_{H1} = \eta_{HR1} = \eta_{HR2} > \eta_{R1} > \eta_{R2}$ where obstacle points have the largest η and the solid fields of R2 have the smallest η.

The total force is:

$$F_{total} = F_{att} + F_{rep} \quad (8)$$

Finally, s_θ is determined by the direction of F_{total}, *i.e.*, s_θ = direction of F_{total}, in the scenarios with LS1, LS2 or LSGR. After getting s_θ, control law proposed in [14] will used to achieve a stable control.

By introducing the priority into potential field function, the higher priority will produce stronger repulsive potential field and larger repulsive force as well. As a result, the robot with lower priority tends not to affect the robot with higher priority, which satisfies both the "Priority Rule" and "Interference Free Rule".

V. SIMULATIONS

In this section, we implement the HCSN using the simulation tools of Pioneer-3 DX, MobileSim. A laser rangefinder LMS200 is assumed to be mounted on Pioneer-3 DX, which uses odometry for localization.

In this scenario, a human is walking from right to left while the robot is moving from the left side to the right side of the corridor. Figure.8 shows the result of HCSN whereas Fig.9 is the result of ND navigation without introducing sensitive field. From Fig.8(a), we can see that at t = 9s, the robot has already started to avoid the human by turning to the upper side of the corridor because it can see the human sensitive field H1, but at about t = 12s, the robot finds that the human is going to the upper side as well. Therefore, the robot is turning to the lower side readily. We can compare the result of using normal ND navigation, as shown in Fig.9. In Fig.9, the robot is still turning to the upper side of the corridor although the human has already turned to the upper side.

In order to quantify the interference to humans and their safety, we define two indices: Interference Index (*II*), which measures the interference to a single human, and Collision Index (*CI*), which measures the safety of human under consideration.

$$II(t) = \frac{1 - |\beta(t)|/\pi}{D_{HR}(t)}$$
$$CI(t) = H\left(\frac{v_h(t)\cos\beta(t) + v_r(t)\cos\phi(t)}{D_{HR}(t)}\right) \quad (10)$$

where $H(x) = \begin{cases} 0 & \text{if } (x < 0) \\ x & \text{if } (x \ge 0) \end{cases} \quad (11)$

The parameters in *II(t)* and *CI(t)* follow Fig.2. Higher value in *II and CI* means more interference and less safe to human.

Figure 8 (b) and (c) shows the profiles of *II(t)* and *CI(t)* of HCSN. The highest values of *II(t)* and *CI(t)* happen near t = 15s, which is 0.0046 and 24, respectively. Compared with the result of navigation without taking sensitive field into consideration, the highest values of *II(t)* and *CI(t)* are now 0.011 and 80, respectively, as shown in Fig.9 (b) and (c), which clearly indicates that our HCSN perform better.

VI. Experimental Results

We have performed experiments to demonstrate the performance of HCSN. In order to construct an MHMR environment, several robots are used as our experimental platform, including Julia, NTU-1, and Pioneer3-DX, as shown in Fig.10. In our experiments, the same Monte-Carlo localization system is used in all three robots for self-positioning. The human tracking system refers to [10]. Moreover, the experimental environment is in MingDa Building of Department of Electrical Engineering, National Taiwan University.

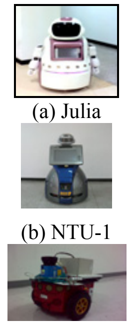
In this experiment, as shown in Fig.11, Julia acts as a “R2” robot which is going to navigate from location (1600, 1250) to location (1050, 2100), NTU-1 is a “HR1” robot and a human is interacting with it at location (1490, 1870), and Pioneer 3-DX is a “R3” robot which goes from location (1330, 2150) to location (1600, 1300). Note that the moving direction of Pioneer 3-DX along its predefined path is just the opposite to that of Julia’s path, and both the maximum speed of Julia and Pioneer is set to be 40cm/s.

Figure.11 shows the trajectories of Julia, NTU-1, Pioneer 3-DX, and humans, and Fig.12 shows the snapshots from the viewpoint of Julia. Julia goes in the middle of the corridor (see snapshot (a) in Fig.12) when it discovers a human, and the sensitive field is sensed so that it starts to avoid entering the sensitive field of the human rather than avoiding him in a close distance (see snapshot (b)). After that, it returns to its path (see snapshot (c)) and avoids disturbing NTU-1, which creates a human-robot stationary joint field (HR1). At the corner, three robots meet together, as shown in snapshot (d) in Fig.12. Since NTU-1 has the highest priority and HR1 is a solid field, both Julia and Pioneer avoid it and try not to interfere with NTU-1. Moreover, the priority of Julia is higher than Pioneer, so Julia is having a relatively larger space, where Pioneer is moving near the HR1. To continue, Julia meets two persons and it still performs a collision free and least interference movement (see snapshot (e) and (f)). In the whole process, all the robots using HCSN obeyed the harmonious rules to provide socially acceptable motions.

VII. Conclusion and Future Work

We have proposed a framework that allows robots harmoniously coexist with humans and other robots. Human-centered sensitive navigation which takes account of harmonious rules, personal space of humans, and working space of robots is proposed. After the robot has successfully tracked people, the sensitive fields are generated. By referring to the sensitive fields in its navigation phase, the robot would make least disturbance to existing humans, behaving more friendly in comparison with the current local navigation approaches. Our approach has been run on different scenarios in both simulations and experiments, and the results showed the feasibility of our human-sensitive navigation.

One of the most common limitations of HCSN is that we have to get the human and robot states to some extent of



(a) Julia (b) NTU-1 (c) Pioneer 3-DX

Fig.10 Experiments platforms

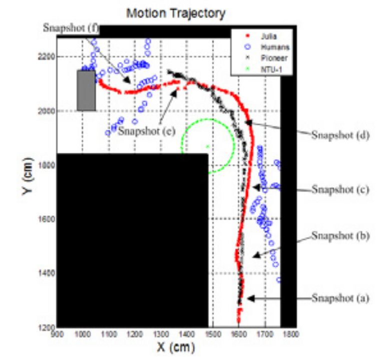
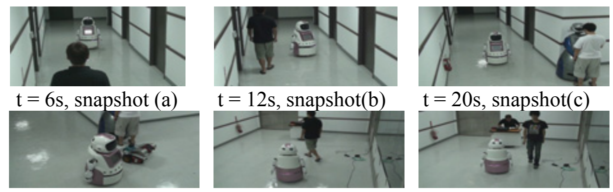


Fig.11 Motion trajectory of robots and humans in experiment 1



t = 6s, snapshot (a) t = 12s, snapshot(b) t = 20s, snapshot(c)

t = 37s, snapshot (d) t = 49s, snapshot(e) t = 56s, snapshot(f)

Fig.12 Experiment 1

precision. The inaccuracy of human tracking will adversely affect the performance of HCSN. Therefore, our future work would be taking account of the tracking error when the robot generates the human sensitive field. In addition, a deadlock may happen when the passage is not large enough. In order to admit this case, we have to extend our rules or to design a mechanism or protocol to cope with such problem.

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