Spatially aware in implicit human robot interaction

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Abstract

Implicit interaction pattern between the human user and the robot is important for reducing cognitive burden and enhancing cooperation effect. Given that the spatially aware is a foundation for human-robot cooperation, for the existing researches of robots, in this paper, a reachable space for a serial robot arm with a fixed monocular vision system and five degrees of freedom (5-DoF) was built. Based on the link frame with D-H notation, analysis and simulating experiments were carried on to show the reachable space in three dimensions. In addition, multi ultrasonic sensors are used to detect the space realizing proximity controlled.

Keywords: Human Robot Cooperation, Spatially Aware, Reachable Space, Proximity Controlled, Implicit Pattern

1 Introduction

With the development of theories and technologies of automatic door is opened in advance. In addition, when we mail to somebody, contact with old friends, call a taxi, Smartphone or tablet PC with iOS, Android, or Windows Mobile system can help us to deal with many things too. Furthermore, in special environment, robot as an intelligent device is wildly used. It is good at repeating jobs or helping people doing something heavy, dangerous, and accurate.

Because of increasing number of devices, human computer interaction (HCI) is particularly important. Given that initiative and attention of devices, HCI can be divided into two types: one is explicit HCI, which is mainly concentrated at present, and the other is implicit one, which is gradually drawing more attention [1-3]. Studies have shown that implicit interaction can replace the explicit one effectively in the interactive process, though implicit interaction is not as accurate as the explicit one [4]. In fact, the recent researches suggest that if taking full advantage of user behaviour contexts as the implicit interactive information, we can do better in the interaction than using explicit information [5, 6].

Implicit human computer interaction (IHCI) is the frontier of the HCI [7]. Nicole Kaiyan, coming from Australia Swinburne University of technology, has put forward the concept of IHCI in 1996, but do not study in detail [8]. Since 2005, universities and institutes in the pervasive computing, more and more intelligent devices appear in our life. When we leave home, road condition signs always direct us. When we entry a building, an United States, Germany, China, Austria and so on, have concentrated on the IHCI theories, technologies and applications. Albrecht Schmidt, coming from Karlsruhe University, carried out related researches on IHCI earlier. Given that two elements of the implicit interactions are perception and reasoning, he proposed that context information was extremely important to the interactive process, and modelled the interaction process with XML language at the same time [9, 10]. Andrew Wilson and Nuria Oliver, coming from Microsoft research in the United States, have developed four systems based on the machine vision to study the implicit interaction technology. Since 2007, Tao, coming from Tsinghua University in China, has developed an adaptive visual system to detect and understand user behaviours in order to apply on the implicit interactions [11]. Meanwhile, Tian, coming from Institute of Software in Chinese Academy of Science, studied the characteristics of the implicit interactions in the view of the WIMP user interface [12]. The development of IHCI at home and abroad was reviewed as shown in the Figure 1.

Table 1 compares IHCI researches from different views in details.

While the implicit interaction pattern is applied in the human robot cooperation, called IHRC, the robot can be smarter to work, active to cooperate, easy to understand partners, and safe to persons and itself. For example, when a robot collaborates with a partner, it does not only work by command, but also predict what the partner wants. So implicit interaction pattern is important to realize human robot cooperating. IHRC includes identity controlled, proximity controlled, profile controlled, and context controlled. Given the proximity controlled aspect, we discussed a method to enhance the cooperating safety in human robot cooperation.

The rest of the paper is organized as follows. In Section 2, the manipulator body we analysing is introduced briefly. Section 3 establishes the rear coordinate system of the manipulator firstly, and then analyses its reachable space. Section 4 discusses proximity controlled method based on multi ultrasonic sensors to enhance cooperating safety, which is an important aspect for human robot cooperation. Section 5 provides the conclusions and the future work.

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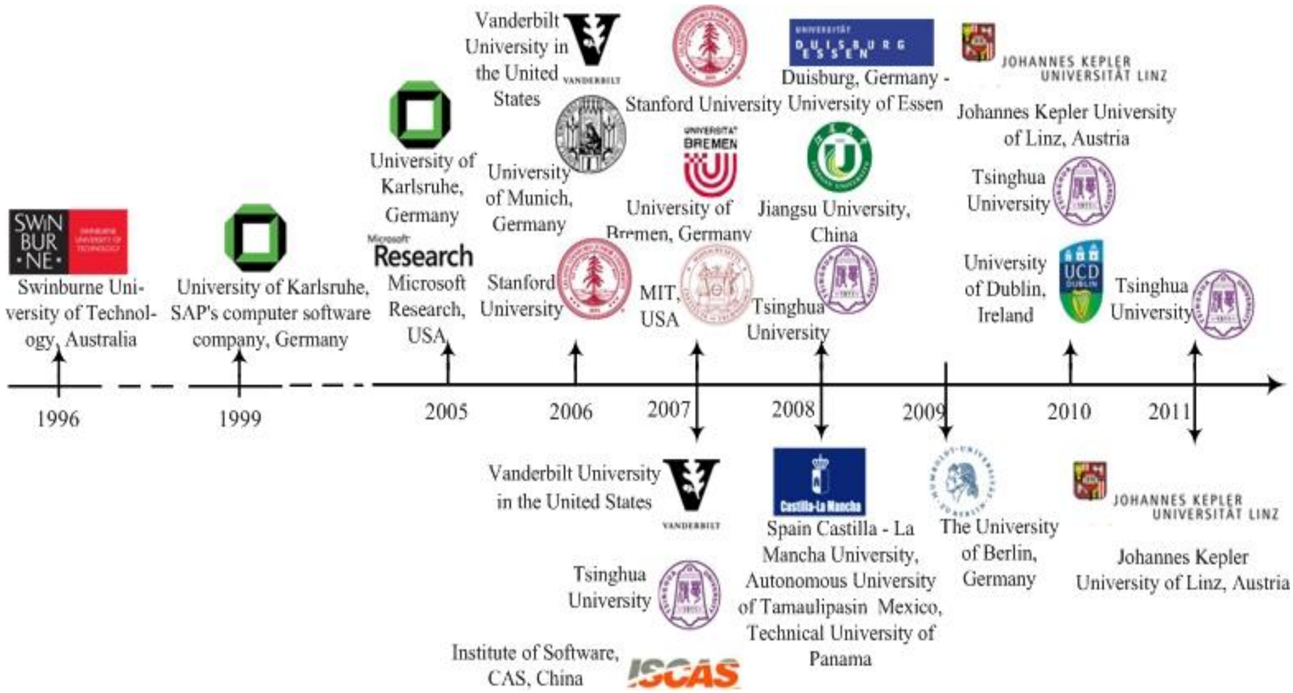

FIGURE 1 Development of ICHI

2 Platform of IHRC

The platform of implicit human robot cooperation is a double-loop system with a joint servo control loop and a vision control loop based on a fixed monocular vision system. It consists of a camera, many types of sensors, a control board, PC, a wireless module and a serial robot arm with five degrees of freedom, as shown in Figure 2.

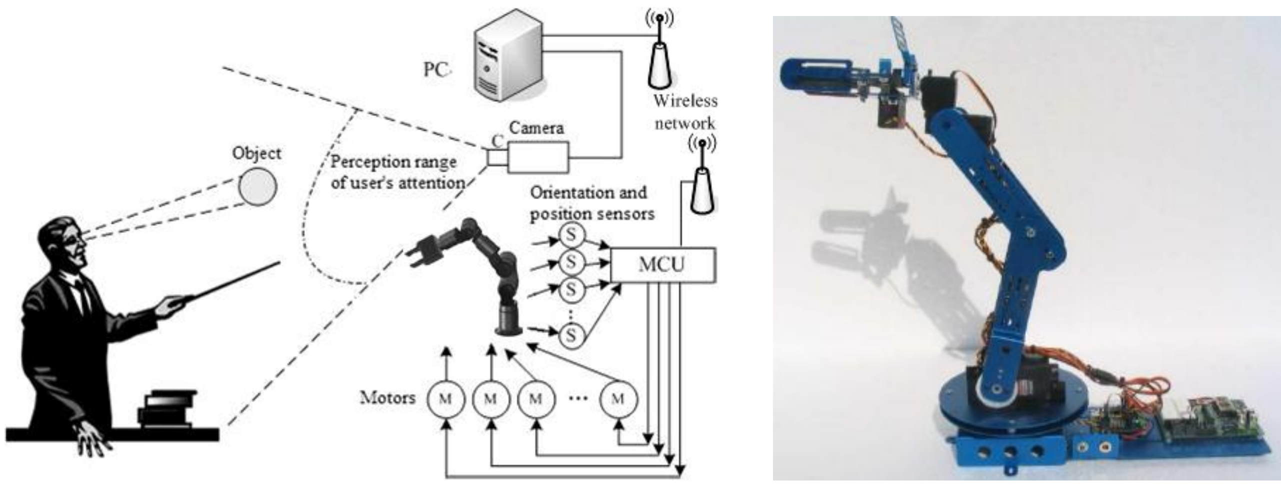

FIGURE 2 Hardware platform of IHRC

3 Reachable space of human robot cooperation

3.1 BODY COORDINATE SYSTEM OF ROBOT ARM

The rear coordinate system of the robot arm is establishes. There are six coordinate systems in total. They are $O_0X_0Y_0Z_0$, $O_1X_1Y_1Z_1$, $O_2X_2Y_2Z_2$, $O_3X_3Y_3Z_3$, $O_4X_4Y_4Z_4$, $O_5X_5Y_5Z_5$, where $O_0X_0Y_0Z_0$ coincides with the world coordinate system as shown in Figure 3.

TABLE 1 Features of domestic and foreign IHCI

Type	Researchers	Contents	View	Context	Sensors	Continuity
Theory	M.J O'Grady, J Ye[13]	Context reasoning, embedded agents, middleware	-	-	-	-
	J Wendy, L Larry[14]	Mode, frame, type	-	-	-	-
	N Kaiyan[8]	Implicit theories	-	-	-	-
	A Schmidt[7]	Definition, identification, modelling, context-aware	-	-	-	-
	H Sebastien, S Ron[15]	Bayes Factor model for explicit and implicit interaction	-	-	-	-
	R Pramila[16]	Implicit human-computer interaction framework	User	Affection	Physiology	**Continuous**
	Li Feng, Pei Jun [17]	Adaptive user interest model	User	Action	Mouse	**Discrete**
	Tian Feng, Deng Changzhi [12]	Post-WIMP Interface Interactive tasks Generation	User	Action	Pen	**Discrete**
	Wang Guojian, Tao Linmi[11]	Shared services model, distributed vision systems	User	Action	Video	**Continuous**
Application	W Hendrik[18]	Get workers' behaviours	User	Action	Angle	**Discrete**
	J Wan, M J O'Grady[19]	Implicit health monitoring	User	Physiology	Physiology	**Continuous**
	H Drewes, A Schmidt[20]	Interaction based on sight	User	Sight	Video	**Discrete**
	W Andrew, O Nuria[10]	Implicit interaction based on gesture	User	Action	Video	**Discrete**
	J Wendy, A L Brian[21]	Whiteboard	User	Position	IR	**Discrete**
	A Riener[22]	Auxiliary Driving	User	Body gesture	Pressure	**Discrete**
	E A Arroyo[23]	The establishment of a task interference management model	User	Sight	Video	**Discrete**
	A Richard, W Monika[24]	Web usability enhancements based on implicit interaction	User	Action	Mouse	**Discrete**
	A Schmidt, H W Gellersen[25]	Input problem in wearable computing	Environment	Item Specifics	RFID	**Discrete**
	J Bravo, R Hervás[26]	Implicit interaction based on RFID and NFC	Environment	Position	RFID	**Discrete**
	R Pramila, S Nilanjan[16]	Implicit interaction between human and robot	User	Affection	Physiology	**Continuous**
	P Dai, L M Tao, et al[27]	Adaptive vision system for meeting	User	Action, complexion	Video	**Discrete**
	Ye Xiyong, Tao Linmi[28]	Implicit interaction based on the action understanding	User	Action	Video	**Discrete**

Based on the established D-H coordinate system of the robot arm, D-H parameters and the joint variables of each link are shown in Table 2. According to parameters above and D-H formulas:

$$ {}^0_1T = \begin{bmatrix} c\theta_1 & 0 & -s\theta_1 & 0 \\ s\theta_1 & 0 & c\theta_1 & 0 \\ 0 & -1 & 0 & d_1 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (1) $$

$$ {}^1_2T = \begin{bmatrix} c\theta_2 & -s\theta_2 & 0 & a_2 \cdot c\theta_2 \\ s\theta_2 & c\theta_2 & 0 & a_2 \cdot s\theta_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (2) $$

$$ {}^2_3T = \begin{bmatrix} c\theta_3 & -s\theta_3 & 0 & a_3 \cdot c\theta_3 \\ s\theta_3 & c\theta_3 & 0 & a_3 \cdot s\theta_3 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (3) $$

$$ {}^3_4T = \begin{bmatrix} c\theta_4 & 0 & -s\theta_4 & 0 \\ s\theta_4 & 0 & c\theta_4 & 0 \\ 0 & -1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (4) $$

$$ {}^4_5T = \begin{bmatrix} c\theta_5 & -s\theta_5 & 0 & 0 \\ s\theta_5 & c\theta_5 & 0 & 0 \\ 0 & 0 & 1 & d_5 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad (5) $$

where s denotes $\sin(\cdot)$, and c denotes $\cos(\cdot)$. Multiply each link matrix to obtain the posture and orientation of the end effecter of the robot arm in the world coordinate system.

$$ {}^0_5T = {}^0_1T \cdot {}^1_2T \cdot {}^2_3T \cdot {}^3_4T \cdot {}^4_5T . \quad (6) $$

Thus, by solving inverse kinematics, joint variables of the robot arm can be calculated with the posture and orientation of the end effecter.

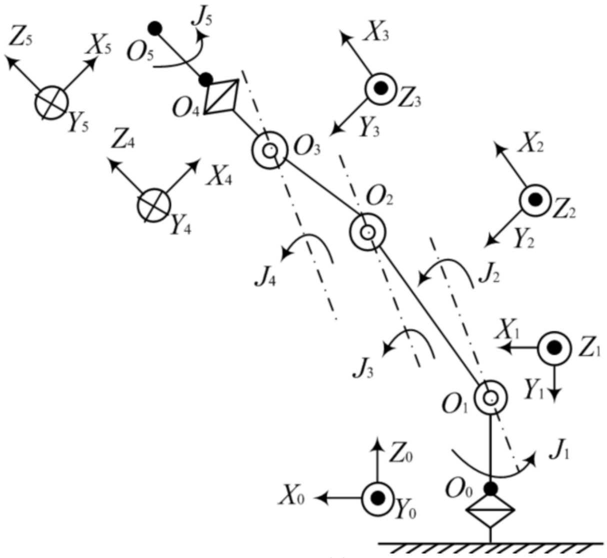

FIGURE 3 D-H coordinate of facial expression robot

TABLE 2 D-H parameter of Arm

Joint i	α_i **/degree**	a_i **/mm**	d_i **/mm**	θ_i **/degree**
1	-90	0	38	$\theta_1 \in [-90,90]$
2	0	154	0	$\theta_2 \in [-180,0]$
3	0	122	0	$\theta_3 \in [-30,150]$
4	-90	0	0	$\theta_4 \in [-180,0]$
5	0	0	181	$\theta_5 \in [-90,90]$

3.2 ANALYSIS TO THE REACHABLE SPACE

Reachable space of joint attention refers to a maximum range of activities of a reference point in the wrist mechanical interface coordinate system (the end effector coordinate system). Without considering the restrictions for the joint angle, for rotary joints, a fixed reference point P_n is assumed on the robot arm. It rotates around Z_n axis with the end coordinate system $O_nX_nY_nZ_n$ together. And it forms a joint attention reachable sub-space $W_{n-1}(P_n)$ in the coordinate system $O_{n-1}X_{n-1}Y_{n-1}Z_{n-1}$, which is a circle. Then, the movement of linkage $n-1$ drives $W_{n-1}(P_n)$ rotating around Z_{n-1} axis to form another joint attention reachable sub-space $W_{n-2}(P_n)$ in the coordinate system $O_{n-2}X_{n-2}Y_{n-2}Z_{n-2}$, which is a toroid. After that, the movement of linkage $n-2$ drives $W_{n-2}(P_n)$ rotating around Z_{n-2} axis to form another joint attention reachable sub-space $W_{n-3}(P_n)$ in the coordinate system $O_{n-3}X_{n-3}Y_{n-3}Z_{n-3}$, which is a spinning body. Rotate around the former axis continually, the joint attention reachable sub-space of the fixed reference point P_n is also a spinning body. There is a transformation between neighbouring sub-spaces:

$$W_{n-j-1}(P_n) = Rot(z_{n-j}, \theta_{n-j}) \cdot W_{n-j}(P_n) \,, \qquad (7)$$

where, $j = 0,1,\ldots,n-2$.

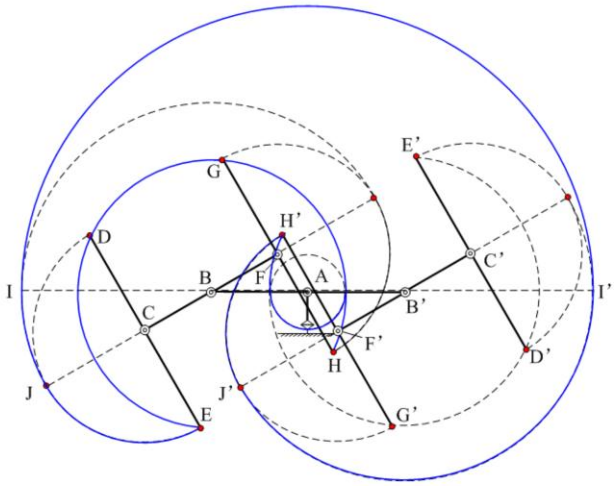

FIGURE 4 Reachable space of joint attention

According to the structure and parameters of the robot arm, $n = 5$. As the statement above, we can get the reachable space of joint attention in human robot cooperating process shown in Figure 4. Due to the rotation axis Z_5 of the wrist joint J_5 is consistent with the linkage, the rotation does not have an impact on the reachable space. Therefore this joint can be ignored. For the rest of joints $J_1 \sim J_4$, firstly, fix $J_1 \sim J_3$ in the extreme position ABC. And rotate the linkage in the permissible range of θ_4 to form arc DJE,$\frown$. Secondly, considering point B as the circle centre, rotate the linkage BC in the permissible range of θ_3 to form a plane encircled by arc EJH,$\frown$ and arc EDH,$\frown$, which is the swept area ρ of arc DJE,$\frown$. Thirdly, considering point A as the circle centre, rotate the linkage AB in the permissible range of θ_2 to form a plane encircled by arc EIH',$\frown$ and arc EDH',$\frown$, which is the swept area σ of the plane ρ. Lastly, joint J_1 rotates in the permissible range of θ_1. Reachable space of joint attention W_1 is obtained.

In the human robot cooperation, the reachable space of joint attention is determined by θ_i. Due to the limitations of the actual structure and driving device, the value of the joint variable is in a certain range, which is:

$$\min(\theta_i) \le \theta_i \le \max(\theta_i) \quad (i = 1,2,\ldots,5) \,. \qquad (8)$$

Suppose that the homogeneous coordinates of the end effecter centre of the robot arm is $\vec{r}_5^{\,P_5} = \begin{bmatrix} x_5^{P_5}(\vec{\theta}_i) & y_5^{P_5}(\vec{\theta}_i) & z_5^{P_5}(\vec{\theta}_i) \end{bmatrix}$ in the coordinate system $O_5X_5Y_5Z_5$, where $\vec{\theta}_i = \begin{bmatrix} \theta_1 & \theta_2 & \ldots & \theta_5 \end{bmatrix}$, and the homogeneous coordinates in the world coordinate system is $\vec{r}_0^{\,P_5}$, which satisfies:

$$\vec{r}_0^{P_5} = {}_5^0T \cdot \vec{r}_5^{P_5} . \quad (9)$$

Therefore, the reachable space of joint attention is the set of $\vec{r}_0^{P_5}$ denoting as:

$$W_1(P_5) = \left\{ \vec{r}_0^{P_5} \middle| \vec{r}_0^{P_5} = \left[x_0^{P_5}(\vec{\theta}_i) \quad y_0^{P_5}(\vec{\theta}_i) \quad z_0^{P_5}(\vec{\theta}_i) \right] \right\}. \quad (10)$$

3.3 REACHABLE SPACE SIMULATION

Based on Monte Carlo method, the reachable space of the robot arm can be simulated. Considering the number of random values for each joint angle is $N = 5000$, the reachable space is shown in Figure 5.

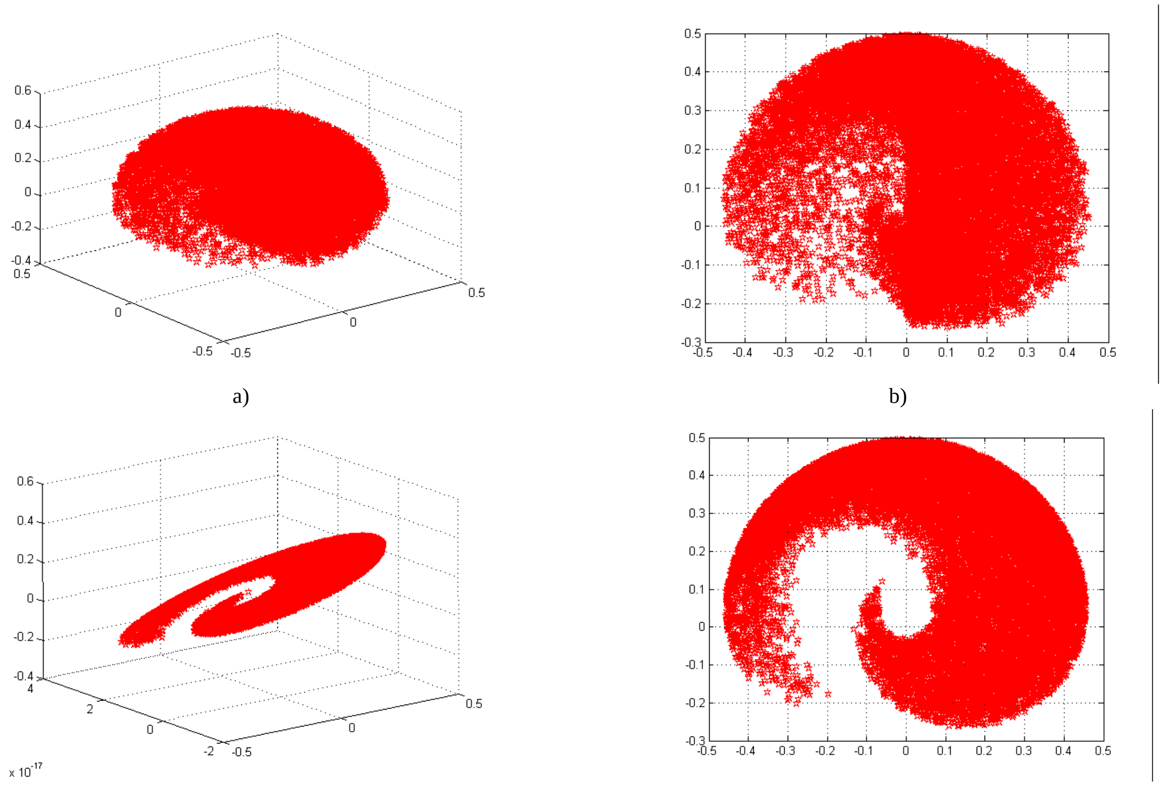

FIGURE 5 The shape of reachable space: a) The view of overall space in three-dimension;, b) The view of overall space in XZ plane projection; c) The view of middle section in three-dimension; d) The view of middle section in XZ plane projection

The movement of each joint forms position cloud atlas of the end effector of the robot arm as shown in Figure 5(a) above. Its shape is similar to an ellipsoid. But due to its internal part is not a complete ellipsoid, the cloud atlas has different density. Its projection in the XZ plane is shown in Figure 5(b). In order to reveal the interior of the reachable space $W_1(P_5)$ of the robot arm, considering that the rotation of the joint 1 only makes position cloud atlas of the end effector shown in Figure 5(a) be symmetrical, draw a middle section $Y = 0$ as Figure 5(c). Figure 5(d) is the projection of the cloud atlas of the middle section to *XZ* plane, which has the same shape and size as Figure 4.

According to the image coordinates of user's attention focus (u, v), the corresponding world coordinates (X, Y, Z) can be calculated. Then solve inverse kinematic equations of the robot arm. In this paper, 8 attention focuses in different directions are considered to obtain joint angles. The results are shown in Table 3.

Based on the Robot Toolbox in Matlab, for 8 conditions stated above, kinematics simulation is carried on. The results are shown in Figure 6.

TABLE 3 Joint angles calculating with image coordinates

No.	Image coordinates (pixel)	World coordinates (mm)	Joint angle (degree)	Attention direction
1	(u,v)=(320,51)	(e,f,g)=(442.6,0,151.7)	[0,-14.4,0,0]	**Above**
2	(u,v)=(320,529)	(e,f,g)=(424.9,0,-130.2)	[0,21.6,0,0]	**Below**
3	(u,v)=(43,240)	(e,f,g)=(424.9,168.2,38)	[21.6,0,0,0]	**Left**
4	(u,v)=(596,240)	(e,f,g)=(424.9,-168.2,38)	[-21.6,0,0,0]	**Right**
5	(u,v)=(596,-131)	(e,f,g)=(384.5,-152.2,232.6)	[-21.6,-25.2,0,0]	**Up right**
6	(u,v)=(43,610)	(e,f,g)=(384.5,152.2,-156.6)	[-21.6,25.2,0,0]	**Bottom right**
7	(u,v)=(186,-111)	(e,f,g)=(406.2,77.5,232.6)	[10.8,-25.2,0,0]	**Up left**
8	**(u,v)=(186,590)**	**(e,f,g)=(406.2,77.5, -156.6)**	**[10.8, 25.2,0,0]**	**Bottom left**

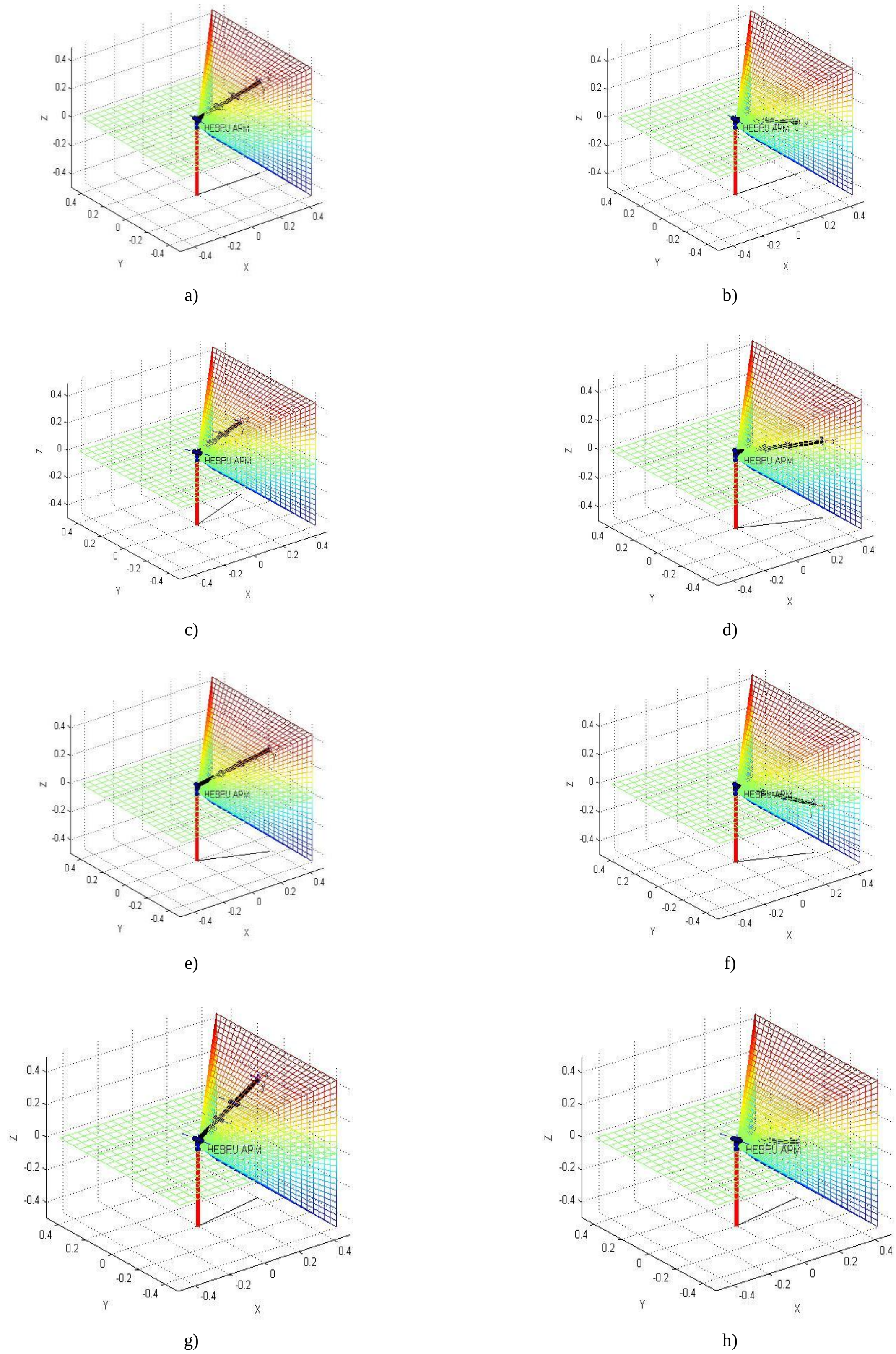

FIGURE 6 Simulation results: a) Above, b) Below, c) Left, d) Right, e) Up-right, f) Bottom-right, g) Up-left, h) Bottom-left

With the method in section 3, we can derive the world coordinates of user's attention from image coordinates. And then solve inverse kinematic equations to get every joint angle. Figure 14 shows results, and manifests that the robot can track user's attention to realize joint attention.

4 Proximity controlled in IHRC

In order to make the human robot cooperating process be safe and effective, proximity controlled problem is considered. Based on multi ultrasonic sensors, we can detect an area, which is the same as the reachable space shown in figure 4. When the robot arm and its partner do one job together, they must share the same intent, attention, and task. So it is necessary to get the accurate positions of each other. On the one hand, proximity controlled keeps the person, who is in the reachable space of the robot arm, safe. On the other hand, the accurate positions information makes the cooperation effective.

In this paper, we use ultrasonic sensor to cover the reachable space. Directivity in sound pressure level of a single sensor is shown in figure 7. From this figure, we can see that its valid detecting angle is 60 degree.

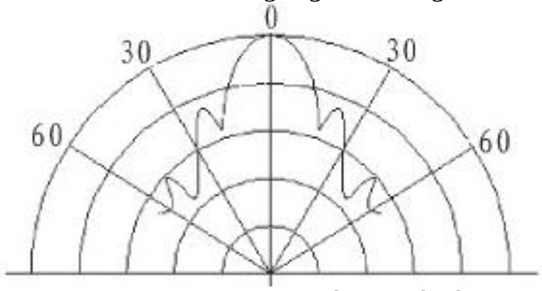

FIGURE 7 Directivity in sound pressure level

We arrange them together one by one as shown in Fgure 8. Therefore, according to the tightness of valid detecting areas, degree of overlap (DoO) is defined, which means the maximum number of overlapped detecting areas. In addition, this index can be represented by the centre distance k of detecting areas. Arrangement of ultrasonic sensors falls into three special types: ***Case 1***, ***Case 2***, and ***Case 3***.

Given that the valid detecting angle of ultrasonic sensor is 60 degree as shown in Figure 7, $\angle MOO_1 = 30^\circ$.

Case 1

In the triangle ΔMOO_1, consider that $OM = a_2 + a_3 + d_5$, so $OO_1 = OM \times \cos \angle MOO_1$, and $MO_1 = OM \times \sin \angle MOO_1$.***Case 1***:

In this case, there is no overlap among detecting areas, so we consider DoO is 0. And centre distance is:

$$k = 2 \times MO_1 = 2 \times OM \times \sin \angle MOO_1 . \quad (11)$$

However, if arranging sensors as Case 1, the middle area among them does not be sensed, this is a blind zone.

Case 2:

In this case, there is maximum degree of overlap in the middle area. DoO is 4. On this condition, the centre distance is:

$$k = MO_1 = OM \times \sin \angle MOO_1 . \quad (12)$$

As we know, if arranging sensors as ***Case 2***, the middle area is overlapped, which uses too many sensors. It is not economic.

Case 3:

In this case, the maximum degree of overlap is 2. And the centre distance is:

$$k = 2 \times PO_1 . \quad (13)$$

According to geometric relations, $PO_1 = \frac{\sqrt{2}}{2} \times MO_1$. So, $k = 2 \times \frac{\sqrt{2}}{2} \times MO_1 = \sqrt{2} \times MO_1$.

Arrangement as ***Case 3*** is a good method. It does not only make full use of the valid detecting angle of every ultrasonic sensor, but also have not any blind zone.

Considering the statement above, on the one hand, while $k \in \left[MO_1, \sqrt{2}MO_1\right]$, the arrangement of ultrasonic sensors seems too tight, this uses too many sensors and disturbs with each other strongly. On the other hand, while $k \in \left[\sqrt{2}MO_1, 2MO_1\right]$, the arrangement of ultrasonic sensors get looser, which make the middle area of sensors be a blind zone. Therefore, $k = \sqrt{2} \times MO_1$, the situation shown in ***Case 3*** is suitable.

For ***Case 3***, the number of ultrasonic sensors could be calculated as follows. Because inner and outer circles are in the same plane, we can obtain that:

$$\begin{aligned} \angle POO_1 &= \arctan\left(PO_1 / OO_1 \right) = \\ &= \arctan\left(\frac{\sqrt{2}}{2} \times OM \times \sin \angle MOO_1 \Big/ OM \times \cos \angle MOO_1 \right) \\ &= \arctan\left(\frac{\sqrt{2}}{2} \times \tan \angle MOO_1 \right) = 22.2^\circ . \end{aligned} \quad (14)$$

Therefore, the number of ultrasonic sensors we needed N is:

$$\begin{aligned} N &= \left[\frac{1}{2} \times \left(\frac{360^\circ}{2\angle POQ} \times \frac{360^\circ}{\angle POQ} - \frac{360^\circ}{\angle POQ} \right) \right] \\ &= \left[\left(\frac{180^\circ}{\angle POQ} \right)^2 - \frac{180^\circ}{\angle POQ} \right] = 12. \end{aligned} \quad (15)$$

Arrange sensors as shown in figure 8(c), and make them work one by one to reduce interference between them. While cooperating, sensors detect and ensure us safe. With the accurate positions, cooperation process will be effective.

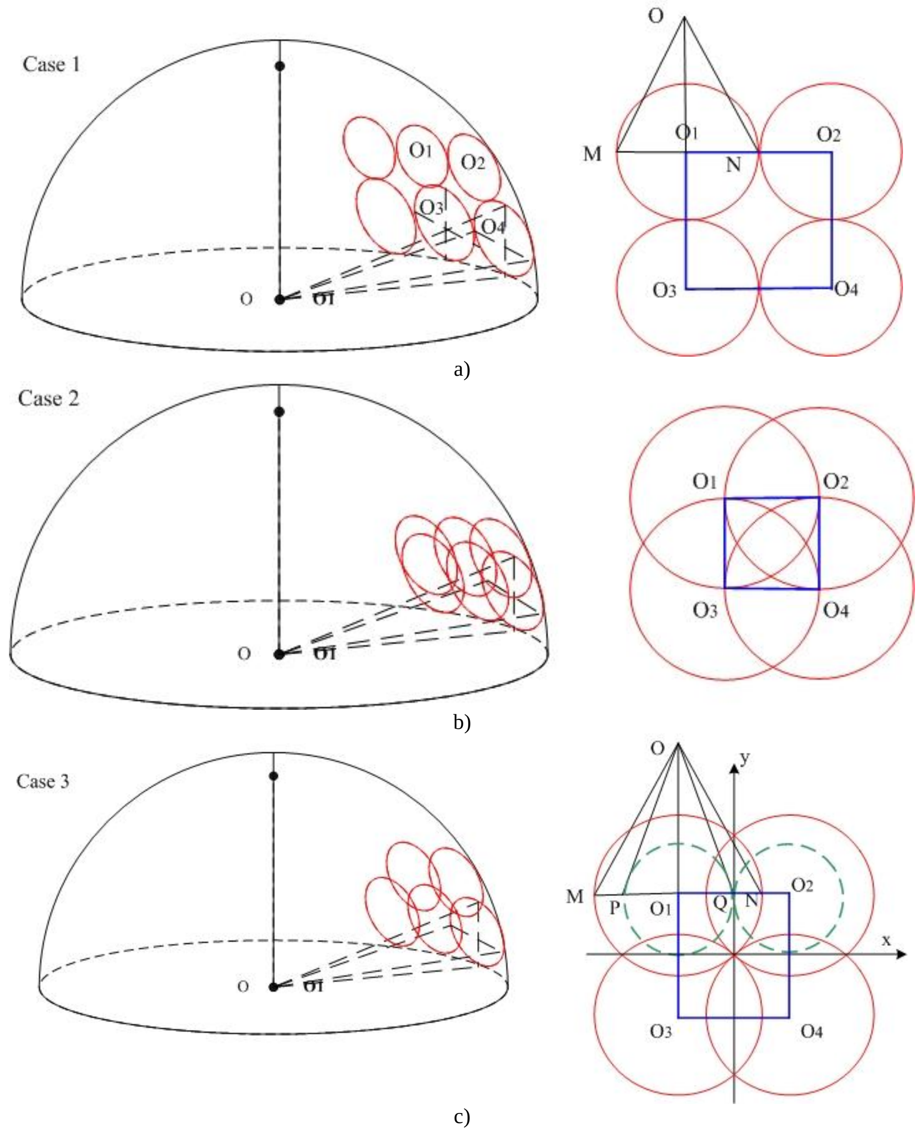

FIGURE 8 Arrangement of ultrasonic sensors: a) Case 1, b) Case 2, c) Case 3

5 Conclusions

1) Proximity controlled in implicit human robot interaction is important. It is not only a key part to realize the effective human robot interaction, but also the foundation of safety.
2) According to the establishment and transform of the coordinate systems, calculation of three-dimensional coordinate, connection of the robot's joints and linkages, and other theories and technologies, reachable space of a robot arm with five degrees of freedom was researched to prepare for human-machine cooperating subsequently.
3) Based on the Robot Toolbox in Matlab, simulation environment for reachable space of the robot arm was built. And analyse the reachable space by simulation.
4) With multi ultrasonic sensors, we establish their applying method, and calculate the number of ultrasonic sensors.

Acknowledgments

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Publications: more than 30 papers
Experience: teaching experience of 3 years, three scientific research projects

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