様　式　C－１９、F－１９－１、Z－１９　（共通）

科学研究費助成事業　　研究成果報告書

令和　４ 年　 ６ 月 ２３ 日現在

機関番号：８２６２６

研究種目：基盤研究(B)（一般）

研究期間：2017～2019

課題番号：１７H０１８０４

研究課題名（和文）次世代協働ロボット：行動神経学に基づく「安心できる」ロボットの動きの解明

研究課題名（英文）Next-generation co-worker robot: Understanding of robot movements perceived safe by humans

研究代表者

山野辺　夏樹（Yamanobe, Natsuki）

国立研究開発法人産業技術総合研究所・情報・人間工学領域・主任研究員

研究者番号：９０４５５４３６

交付決定額（研究期間全体）：（直接経費）　　13,700,000円

研究成果の概要（和文）：人間と空間を共有して作業を行う協働ロボットを対象として、どのようなロボットの動きに対して人間が安心かつ心地よさを感じるのかを明らかにした。手渡しとリーチング作業を代表的な作業として選定し、人間同士/人間－ロボットによる協働作業実験行い、人間の感覚とロボットの動作との関係を調査した。手渡しの際には、自分と相手の位置関係や身体的・社会的特徴を基に相手の動作を推定し、自己の動作を上手く調整していること、近接空間で作業を行う場合は、ロボット動作の不確定性が人間に不快感を与える大きな要因であり、人間の作業動作の変化から不快度を推測できることを示した。

研究成果の学術的意義や社会的意義
本研究の成果は、人間と空間を共有して作業を行う協働ロボットの動作生成やシステムデザインに貢献するものである。例えば物の手渡しを行う場合、本研究で示した位置関係や相手の身体的・社会的モデルに基づいたロボット動作を生成することで、相手に違和感を与えない快適な受け渡しを可能とする。また一緒に作業を行う人間から認識される不確定性を低減するロボット動作やシステムの設計を行うことで、より快適な協働作業を実現する。

研究成果の概要（英文）：In this research, we clarified what kind of robot movements a human feels safe and comfortable with, in human-robot co-worker scenarios. We adopted object handover and arm reaching tasks as typical collaboration ones. Human-human and human-robot collaboration experiments were conducted and the relationships between human feelings and robot movements were explored. For object handover, it was found that humans can estimate their partner’s handover behavior very well based on the physical and social characteristics of their own and their partner. Our experiments also confirmed that the perceived uncertainty in the robot movement is the fundamental determinant of human discomfort when a robot is working in the vicinity of humans. These results can contribute to planning robot motions and comfortable collaboration systems.

研究分野：ロボティクス

キーワード：協働ロボット　行動神経学　動作生成

１．研究開始当初の背景

'Co-worker' scenarios, where robots and humans work closely within each other's workspace, have thus been a topic of great recent interest in the robotics community. For example, major robot companies have developed collaborative robots and several recent research projects have explored robot behaviors in co-worker scenarios. However, these projects and companies have mainly concentrated on robot control for safe, compliant, and efficient human interactions. On the other hand, an additional critical aspect, human perception, has been almost not explored. Even if a robot control is very 'safe', a human will be comfortable with it only if he/she perceives the robot to be safe. However, it has not been shown what aspects of the robot's behavior would enable this trust.

２．研究の目的

In this research, we clarify what kind of robot movements a human feels safe and comfortable with, in manipulator co-worker scenarios. We adopted object handover and arm reaching tasks as typical collaboration ones. Human collaboration experiments were conducted for these tasks and the relationships between human feelings and robot movements were explored by analyzing the obtained experimental data.

３．研究の方法

(1) Object handover

Handovers require one individual's hand to enter the 'peri-personal space' of another individual, which is a space around an individual's body that they are known to be protective of. Studies of peri-personal space have shown that it is affected by an individual's reach and hence we hypothesized that an individual's size and arm length affect comfortable handovers. Intuitively, we hypothesized that social aspects, such as gender and social dominance of individuals, also affect the movements. Here, we focused on and analyzed the location of object transfer-how humans determine it, and whether and how the specific characteristics of interacting partners affect it.

Fig. 1 shows our experiment setup and the whole experiment sequence. Twenty *participants* were asked to give(receive) objects to(from) the same three *representative partners* (*partners* for short) at one of three inter-personal distances (IDs). To examine the role of visual information, the subjects performed handovers in blindfolded and normal situations (shown by No-vision (nVF) and Vision (VF) sessions).

The subjects were divided into two groups, which include 10 participants and 3 partners each, to reduce the burden on partners. The 10 participants in group 1 were all males (age of 23.7±1.3, height of 174±6.7 cm, arm length of 54.7±3.4 cm). They worked with 2 males and a female partner (partner1-male, 23 years, 171 cm height, 52 cm arm length; partner2-male, 25 years, 180 cm height, 58 cm arm length; partner3-female, 22 years, 168 cm height, 55 cm arm length). Group-2 included 4 males (age of 57.0±8.15, height of 169.3±5.12 cm, arm length of 53.0±1.73 cm) and 6 females (age of 42.2±17.1, height of 156.8±3.48 cm, arm length of 50.5±2.29 cm). They worked with 2 males and a female partner (partner1-male, 20 years, 169 cm height, 54.5 cm arm length; partner2-male, 22 years, 181 cm height, 58.5 cm arm length; partner3-female, 20 years, 160 cm height, 50 cm arm length). All participants and partners were right-handed.

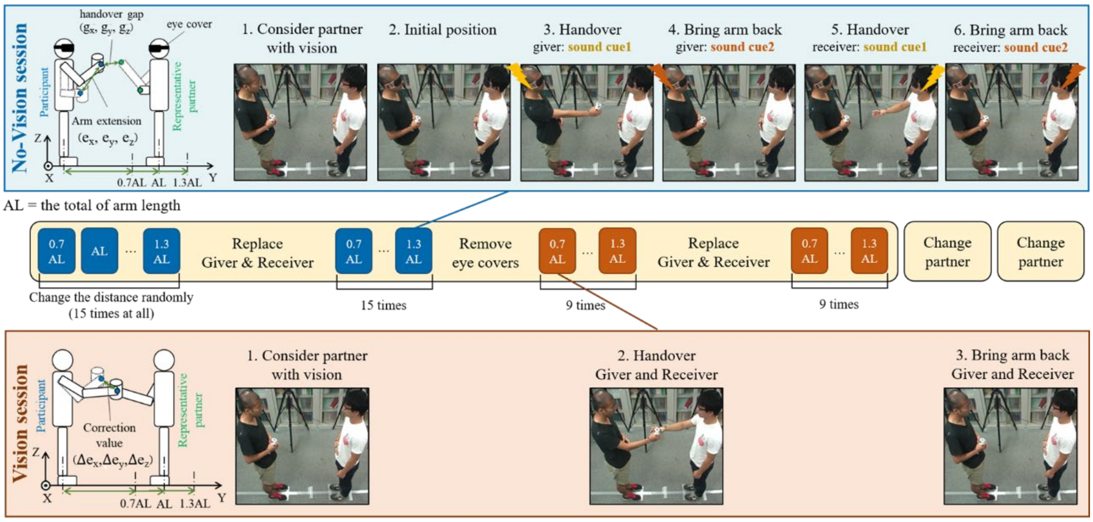


Fig. 1: Experiment sequence for handovers

Three IDs were defined for each pair as 0.7AL, AL, and 1.3AL, where AL is the sum of their arm lengths. The participant and partner were asked to stand at the determined positions, look at each other, and then cover their eyes with an eye cover for nVF sessions. They wore a wireless earbud in their ear and were instructed to make a handover movement when a beep sounds, hold the extended arm and bring the arm back when the second beep sounds. Unknown to subjects, we introduced a delay between the beeps to the participants and partners for nVF sessions to avoid collisions, which ensured that they made their movements one after another. The participants performed nVF sessions first, which include 15 (5×3IDs) handovers, as a giver and a receiver (the order is randomized), and then did VF sessions, which includes 9 (3×3IDs) handovers. After completing both nVF and VF sessions, the participants repeated the whole sequence with other partners. At last, the participants and partners were asked to answer a social dominance orientation questionnaire [1] for measuring their social dominance.

The movements made by the participants were recorded by a motion capture system with reflective markers (on their hand/arm/shoulder), analyzed the systematic changes with each partner, and compared with and without visual feedback.

(2) Arm reaching task

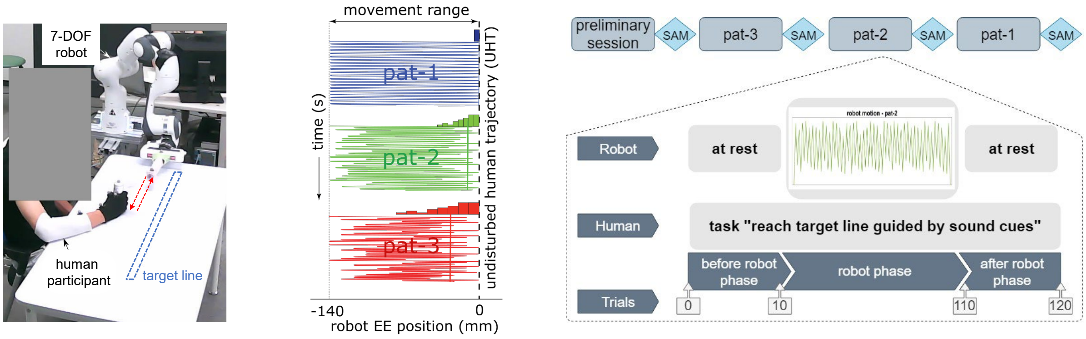
Here, we concentrated on the robot movements working in the vicinity of humans because humans will feel more uncomfortable when a robot is very close enough to collide with them. We considered four different models of human discomfort and designed an empirical human-robot co-worker task to quantify the discomfort experienced by the human by analyzing behavioral changes and to examine which model of discomfort explains the changes best.

For defining our discomfort model, we first defined the undisturbed human trajectory (UHT) as a human movement trajectory when performing his/her task without disturbance from a robot co-worker. Then, the following four discomfort models were constructed using the position of the robot end-effector relative to the UHT as a parameter based on previous human behavioral studies and our intuition.

- Robot Proximity (RP) model: the proximity of the robot to the UHT is the key determinant,
- Robot Velocity (RV) model: the velocity of the robot movement is the key determinant,
- Robot Range (RR) model: the range of the robot movement is the key determinant, and
- Robot Uncertainty (RU) model: the perceived uncertainty of the robot movement is the key determinant. The standard deviation of the distance when the robot is closest to the human is considered.

Fig. 2-(a) shows our experiment setup. The participants sat on a chair in front of a table, on which the start point and the target line were shown. A 7-degrees of freedom robot was installed on a stand on the left side of the table. The robot grabbed a stick covered with soft material and moved the end-effector back and forth to the UTH during the experiments. The participants were instructed to repeat the movement of sliding their hand on the table from the start point to a goal on the target line while holding a stick. They were asked to make a 'one shot' reaching movement (without stops) to the target line while avoiding bumping into the robot. Any point on the target line could be freely selected for each movement. A repetitive pattern of beeps was utilized to instruct the participants on when to start and complete their reaches. Based on the beeps, each reaching movement was repeated every second. The timing of beeps was designed to synchronize the human movement with the robot movement, such that the robot would sufficiently interfere and potentially cause them discomfort.

We designed three robot movement patterns to qualitatively distinguish the key determinant of discomfort by using our four discomfort models (Fig. 2-(b)). The patterns were determined by the three parameters: the minimum/maximum distances of the robot end-effector from the UHT and the variation in the two parameters mentioned above. For pat-1 to 3, we set the same values to the



(a) Experiment setup (b) Robot movement patterns (c) Experiment sequence

Fig. 2: Experiment settings for arm reaching task

minimum/maximum distances but set the different values to the variation, 0mm, 40mm, and 80mm, respectively. The average minimum distance of the robot from the UHT is the smallest in pat-1 and becomes large in pat-2 and 3. Therefore, the RP model predicts that the discomfort is highest for pat-1, less for pat-2, and the least for pat-3. For the velocity, the mean speed of the robot end-effector is highest for pat-1 because we set the same peak speed in all the patterns and it remains at the peak speed for a longer time for longer movement. The RV model thus predicts the highest discomfort for pat-1, less for pat-2, and the least for pat-3. The RR model predicts the same discomfort for all patterns because the movement ranges are the same. The RU model, which is determined by the standard deviation of the minimum distance, predicts that the discomfort is minimal for pat-1, progressively more for pat-2, and the highest for pat-3.

Fig. 2-(c) presents the experiment sequence, which includes four sessions. The first one served as a preliminary session to accustom the participants to follow the sound cues while working in the proximity of the disturbing robot, which moved far away compared with the following three experimental sessions. Each experimental session was divided into three phases (of 10, 100, and 10 trials) with and without robot disturbances. The robot movement patterns were selected randomly for each session. After a session, the participants were asked to answer the Self-Assessment Manikin (SAM) [2] survey to assess their emotional state during the corresponding session. 21 participants (15 males, 6 females of 14 nationalities, aged 20-43, mean 27.9± SD 6.32) joined in the experiment. The arm movements made by the participants and the positions of the sticks were recorded by a motion capture system with reflective markers.

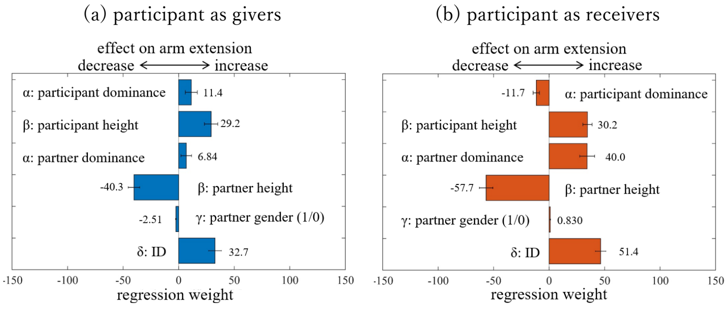
All experiments conducted in this research were approved by the local ethics committee at the National Institute of Advanced Industrial Science and Technology (AIST). All participants were naive to the motive of the experiment and gave informed consent to participate in the study.

４．研究成果

(1) Object handover

To investigate how the handovers were changed when the participants were givers and receivers, with or without visual feedback, with respect to the characteristics of them and their partners, we looked at the following three parameters: arm extension ($e_{x,y,z}$: defined how much the participant extended their arm in the nVF sessions during a handover), handover gap ($g_{x,y,z}$: defined as the absolute difference between the hand positions of the giver and receiver in the nVF sessions), correction ($\Delta e_{x,y,z}$: defined as the difference between the positions of participant's hand at the end of their handover in the nVF session and in the VF session). Here, the hand position was determined by the position of the reflective marker attached to the MP joint.

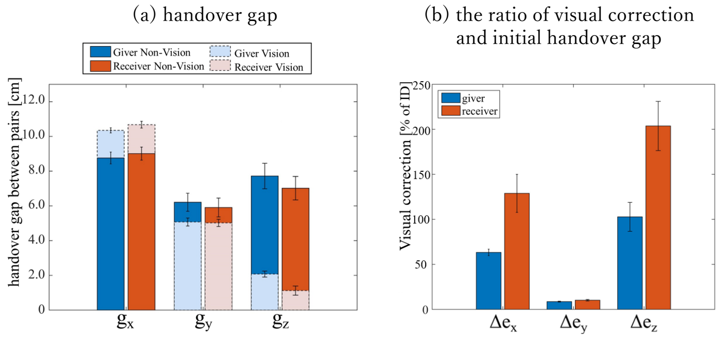
We first performed a 2-way ANOVA of the arm extensions on the factors 'ID' and 'partner'. A significant main effect of 'ID' was observed on the arm extensions. Interestingly, a significant main effect of 'partner' on the arm extension towards the partner (e_y) was also observed. The results show that the participants clearly modulated their handover behavior in the 3D space to account for the IDs and also modulated their anterior-posterior arm extension (e_y) systematically according to the partner they interacted with.


(a) participant as givers

(b) participant as receivers

Fig.3 Regression weights for the model of anterior-posterior arm extension e_y

Then, we created linear regression models for the anterior-posterior arm extension (e_y) to investigate what aspect of the partner's features affects the handover behavior. By using the Akaike Information Criteria (AIC), we found that the model with parameters of both the participant's own and his partner's features (height, gender, and dominance) and


(a) handover gap

(b) the ratio of visual correction and initial handover gap

Fig. 4: Handover gaps and visual correction

the ID, can explain the arm extensions very well. Gender was set to 0 when the gender of the participant and the partner were the same and 1 when they were different. Arm length was not used because it was correlated with height.

Fig. 3 shows the regression weights on each factor. As predicted by the ANOVA, the participants modulated their e_y with ID both as a giver and receiver. As a common tendency for both givers and receivers, it is confirmed that the participants extended their arms when their own height is high or the partner's dominance is high; the arms were extended less when the partner is tall; the gender has little effect on the arm extensions. Interestingly, the participants' own dominance led to an increase of e_y as a giver, but a decrease of e_y as a receiver. Fig. 4 shows the handover gap ($g_{x,y,z}$) and the correction ($\Delta e_{x,y,z}$). In the extension direction, the gap (g_y) is small in the nVF sessions, and the correction (Δe_y) is also small. On the other hand, the gap for the z-axis direction (g_z) in the nVF sessions and the correction (Δe_z) are large. From these results, it can be confirmed that humans can estimate the anterior-posterior handover position of their partner, and as a consequence, adjust their hand position to meet their partner's hand. The prediction based on the partner's model is mainly utilized for the anterior-posterior movements, while the adjustment using visual feedback occurs for the other directions during handovers. These insights are very crucial for the design of robot handovers. For example, it is sufficient for robots to control mediolateral and inferior-superior handover movements by visual servoing, but for making anterior-posterior movements, robots need to have a good understanding of human behavior. Our linear regression model will help to improve the understanding.

(2) Arm reaching task

During the experiments, we observed that the participants performed a straight-line reach when the robot stopped, but their reach deviated away from the robot when it came close to them in the robot phase. Fig. 5 shows a sample of subject trajectories in the robot phase. There were differences in the trajectory deviations depending on the robot movement patterns. We performed a 2-way ANOVA of the deviations on the factors 'pattern' and 'trial' between the 11th and 100th trials in the robot phase (the first 10 trials were omitted for the stabilization of the trajectories). As a significant main effect of 'pattern' was observed but 'trial' and the interaction were not, we adopted the median trajectory deviations for each pattern to quantify the trajectory deviations. In addition, we found a strong correlation between the median trajectory deviation and the anxiety reported by the subjects in the SAM questionnaire. These allowed us to use the median trajectory deviation as a behavioral measure of the discomfort perceived by the participants.

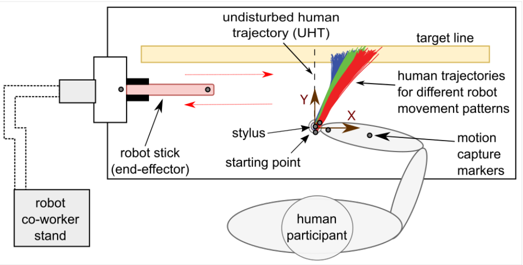


Fig.5: Sample plots of trajectory deviations

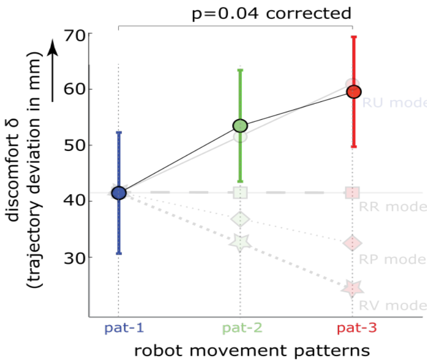


Fig. 6: Model validation. The median trajectory deviations are superimposed over our discomfort model trend plots.

In Fig. 6, the across-subject median trajectory deviations were plotted. Comparing the result with our discomfort models, it was shown that the RU model can clearly explain the data. Our experiments thus confirmed that uncertainty in the robot movement was the fundamental determinant of human discomfort. Previous studies in social neuroscience as well as for robot trust, have observed that the 'trust' felt by a human towards interacting agents is influenced by the predictability of the agents' behavior, especially for their decision-making. Here, we clearly show that by using behavioral measures, uncertainty is also critical at the level of robot movement in human-robot co-worker scenarios. It is also important to note that the human discomfort observed here is modulated not by the robot movement uncertainty itself, but rather by the perceived robot movement uncertainty by humans. The result can contribute to planning robot motions working in the vicinity of human workers.

[1] F. Pratto et al.: "Social dominance orientation: A personality variables predicting social and political attitudes," J. of Personality and Social Psychology, vol. 67, no. 4, pp. 741-763, 1994.
[2] M. M. Bradley and P. J. Lang: Measuring emotion: The self-assessment manikin and the semantic differential, J. of Behavior Therapy and Experimental Psychiatry, vol. 25, no. 1, pp. 49–59, 1994.

５．主な発表論文等

〔雑誌論文〕　計1件（うち査読付論文　1件／うち国際共著　0件／うちオープンアクセス　1件）

１．著者名 Kato Saki、Yamanobe Natsuki、Venture Gentiane、Yoshida Eiichi、Ganesh Gowrishankar	４．巻 14
２．論文標題 The where of handovers by humans: Effect of partner characteristics, distance and visual feedback	５．発行年 2019年
３．雑誌名 PLOS ONE	６．最初と最後の頁 e0217129
掲載論文のDOI（デジタルオブジェクト識別子） 10.1371/journal.pone.0217129	査読の有無 有
オープンアクセス オープンアクセスとしている（また、その予定である）	国際共著 －

〔学会発表〕　計3件（うち招待講演　1件／うち国際学会　3件）

１．発表者名 Kato Saki、Yamanobe Natsuki、Venture Gentiane、Ganesh Gowrishankar
２．発表標題 Humans Can Predict Where Their Partner Would Make a Handover
３．学会等名 The 13th Annual ACM/IEEE International Conference on Human Robot Interaction, Late-Breaking Reports（国際学会）
４．発表年 2018年

１．発表者名 Heraiz-Bekkis Daphne、Ganesh Gowrishankar、Yoshida Eiichi、Yamanobe Natsuki
２．発表標題 Robot movement uncertainty determines human discomfort in co-worker scenarios
３．学会等名 International Conference on Control, Automation and Robotics (ICCAR 2020)（国際学会）
４．発表年 2020年

１．発表者名 Yamanobe Natsuki
２．発表標題 How should robots move to work together with humans?
３．学会等名 23rd CISM IFToMM Symposium on Robot Design, Dynamics and Control（招待講演）（国際学会）
４．発表年 2020年

〔図書〕　計0件

〔産業財産権〕

〔その他〕

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６．研究組織

	氏名 （ローマ字氏名） （研究者番号）	所属研究機関・部局・職 （機関番号）	備考
研究分担者	GOWRISHANKAR. G (Ganesh Gowrishankar) (10570244)	国立研究開発法人産業技術総合研究所・情報・人間工学領域・客員研究員 (82626)	
研究分担者	吉田　英一 (Yoshida Eiichi) (30358329)	国立研究開発法人産業技術総合研究所・情報・人間工学領域・研究部門付 (82626)	
研究分担者	Venture Gentiane (Venture Gentiane) (30538278)	国立研究開発法人産業技術総合研究所・情報・人間工学領域・特定フェロー (82626)	

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８．本研究に関連して実施した国際共同研究の実施状況

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