Dyadic Human-Human Interactions in Reaching Tasks: Fitts' Law for Two*

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Abstract. In this paper we examined physical collaboration between two individuals using a dual-arm robot as a haptic interface. First we design a haptic controller based on a virtual dynamic model of the robot arms. Then we analyze dyadic human-human collaboration with a reaching task on a 2D plane, where the distance and size of the target changed randomly from a pool of nine reachable positions and sizes. Each subject performed the task individually and linked through the guided robot arms with a virtual model to perform the same task in collaboration. We evaluated both individual and collaborative performances based on Fitts' law, which describes the relation between the speed of motion and its accuracy. The results show that the Fitts' law applies both on individual and collaborative tasks, with their performance improving when in collaboration.

Keywords: Virtual dynamic model · Human-human interaction · Fitts' law

1 Introduction

With rapid advances in robotics, robots are slowly expanding from industrial environment, where they were isolated from humans into environments where they must work side-by-side with people. This drives researchers to turn their attention to the field of human-robot collaboration, with studies such as [4],[5],[9],[12]. To better understand human-robot collaboration we must first however understand how humans collaborate with each other. In the past two decades several studies have been conducted on this topic [1],[3],[8],[11]. In a study published in 2014 by G. Ganesh et al. [3] it was discovered, that subjects in collaboration were able to learn the task better than subjects who practised the task alone for the same duration. It was also stated, that the subject's improvement was most prominent when their partner was similar to them, meaning an interaction with a human is more beneficial than with a non-human agent (i.e. a robot) and the same applying for difference in social status — i.e. collaboration with a peer is more beneficial than with an expert or a higher-up. Knowing this our goal is to

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improve human-robot collaboration by integrating properties of human movement into the robot control, thus making the robot task perform similarly to human task performance.

In one of our previous study we suggested a novel method for on-line adaptation of robotic trajectories using Iterative Learning Controller framework [7]. In this method the robot adapts to the human motion by taking into account the Fitts' law. Fitts' law is a well known phenomena, which describes the trade-off between speed of motion and accuracy in human task performance [2]. Similarly in our study [6] we suggested improving human-robot interaction by exploiting the mechanical capabilities of robots and combining them with cognitive and perception capabilities of humans.

In the aforementioned studies, the main task for the robot was to follow the human actions and improve their accuracy. In a similar light, we suggest that the robot should improve accuracy of human actions however, not by following the human action but by estimating the collective goal beforehand. This suggestion is based on a study of human-human interaction done by A. Takagi et al. in 2019 [8] where they discovered that a group of individuals coordinate their movement by estimating the collective goal, making physical interaction beneficial. This can be achieved by first studying how humans change their movement to achieve the collective goal. For this we designed a novel haptic interface using dual-arm robots.

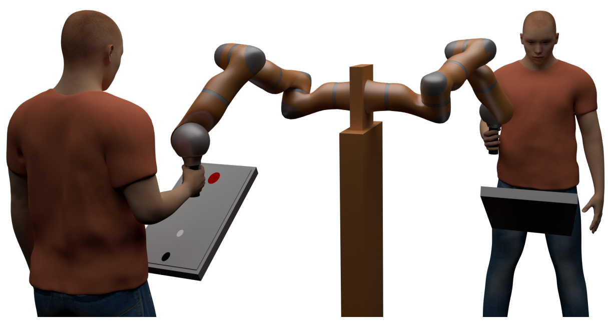


Fig. 1. Experimental setup of the study. Each subject was tasked to stand in front of a screen and manipulate the robot arm's end effector so that they reach the target displayed on the screen.

In this paper we first describe in section 2 the design of the dual-arm robot haptic interface, used for future studies on human-human and human-robot collaboration. In section 3, we then evaluate the control framework by conducting a preliminary evaluation using one subject group, where each subject performing a 2D reaching task individually and in collaboration. In section 4 we discuss the impact of our work.

2 Control method

In this section we first give a short overview of the control design for a haptic interface. Haptic interface is based on a two Kuka LWR with the same initial joint configuration. To convert a redundant robot arm into a haptic interface we designed a new robot controller based on a virtual dynamic model of the robot arms [10]. The robot arms were equipped with a force sensor at the end-effector and a handle for enabling human guiding.

2.1 Virtual dynamic model

The virtual dynamic model consists of two rigid body points, each representing one end-effector of the dual-arm robot, coupled together by a spring. To assure movement of the dynamic model, a translation joint is added to the spring's midpoint.

When force is applied to an end-effector, the dynamic model reacts by generating a proportional force to the joint. The proportional force $\boldsymbol{F}$ is described as

$$\boldsymbol{F} = \boldsymbol{F_r} + \boldsymbol{F_l} + \boldsymbol{F_k}, \tag{1}$$

where $\boldsymbol{F}_r$ is the force applied to the right end effector, $\boldsymbol{F}_l$ the force applied to the left end effector and $\boldsymbol{F}_k$ the force of the spring.

The force $\boldsymbol{F_k}$ is based on Hooke's law and is described as $\boldsymbol{F_k} = K(\boldsymbol{l} - \boldsymbol{l_d})$, where $\boldsymbol{l}$ is the distance between the end-effector, $\boldsymbol{l_d}$ is the desired distance and K is the stiffness coefficient of the spring.

Assuming the stiffness coefficient K is large, the spring imitates a rigid bar which connects the two end-effectors and ensures a constant distance between them. Therefore the force $\boldsymbol{F_k}$ can be neglected, and Eq. 1 results in:

$$\boldsymbol{F} = \boldsymbol{F_r} + \boldsymbol{F_l}. \tag{2}$$

The desired Cartesian position of the end effectors can be calculated based on the proportional force $\boldsymbol{F}$. Using Newton's second law of motion we can describe the relation between force and movement as

$$\boldsymbol{F} = m\ddot{\boldsymbol{x}}, \tag{3}$$

where m equals point's virtual mass and $\ddot{\boldsymbol{x}}$ equals acceleration.

In real dynamic systems friction, or damping, slows the motion. To simulate this we complemented Newton's second law of motion by adding damping to our dynamic model, giving us a dynamical system described as

$$\boldsymbol{F} = m\ddot{\boldsymbol{x}} + D\dot{\boldsymbol{x}}, \tag{4}$$

where D is a damping constant.

To calculate the desired acceleration of the end-effector, we can solve Eq. 4 for the variable $\ddot{\boldsymbol{x}}$ and is governed by

$$\ddot{\boldsymbol{x}}_{\boldsymbol{d}} = K_p\boldsymbol{F} - K_d\dot{\boldsymbol{x}}_{\boldsymbol{d}}. \tag{5}$$

Here, K_p is a proportional coefficient and equals $\frac{1}{m}$ and K_d is a derivative constants, which equals $\frac{D}{m}$.

This model is used with both the left and right robot arm coupled together, as well as for each arm individually. In the latter case the force is read only from the arm that is being used and the forces from the other arm are assumed to be 0. This means that the proportional force F equals the sensed force on the end effector of the active robot arm.

2.2 Robot control

The robot arm is controlled on a velocity level, with the desired end-effector velocity as input from the virtual dynamic model. Its inverse kinematics can be given as

$$\dot{\boldsymbol{q}} = \mathbf{J}^{\dagger}\dot{\boldsymbol{x}}_c + \mathbf{N}\dot{\boldsymbol{q}}_n, \tag{6}$$

where $\mathbf{J}^{\dagger}$ is Moore-Penrose pseudo inverse of Jacobian matrix $\mathbf{J}$, defined as $\mathbf{J}^{\dagger} = \mathbf{J}^T(\mathbf{J}\mathbf{J}^T)^{-1}$, $\dot{\boldsymbol{x}}_c$ is the end effector velocity, $\mathbf{N}$ is the null-space matrix of $\mathbf{J}^{\dagger}$, and $\dot{\boldsymbol{q}}_n$ is an arbitrary joint-space velocity vector.

The null-space joint space velocity $\dot{\boldsymbol{q}}_n$, which maintains the desired robot posture, is defined with

$$\dot{\boldsymbol{q}}_n = K_N(\boldsymbol{q}_0 - \boldsymbol{q}), \tag{7}$$

where K_n is a scalar gain, $\boldsymbol{q}_0$ are desired joint positions (desired posture) and $\boldsymbol{q}$ current joint positions.

Cartesian controller with feed-forward control is used for determining the end-effector velocity and is defined as

$$\dot{\boldsymbol{x}}_c = K(\boldsymbol{x_d} - \boldsymbol{x_r}) + \dot{\boldsymbol{x}}_{\boldsymbol{d}}, \tag{8}$$

where K is a scalar gain and $\boldsymbol{x_r}$ is the actual position of the end-effector.

3 Preliminary Evaluation

A preliminary evaluation of human-human collaboration was conducted, using the control method described in section 2. For this, we used two male volunteers. Both subjects were right-handed. As a baseline, the experiment was first conducted for each subject individually, using only one robot arm as a haptic interface. Afterwards, the robot arms were coupled together and the experiment was conducted again, this time with the subjects collaborating to reach the same goal.

3.1 User interface

To conduct the experiment a simple graphic user interface (GUI), shown in Fig. 2 was created. The black dot is the starting position which the subjects must reach to start the experimental session, the red dot is the target, whose size and position is chosen randomly from a pool of nine reachable positions and sizes. The white dot is the moving point, which the subjects control through the haptic interface. For the individual experiments its position correlates to the end effector's position in world space, while in the collaboration experiment its position was calculated as the midpoint between the two end effectors.

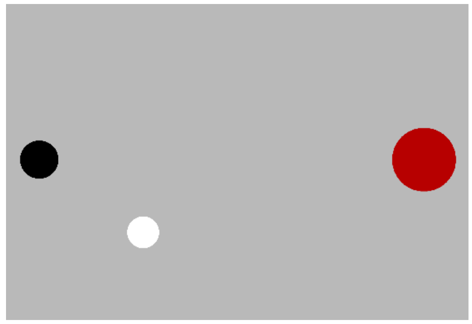


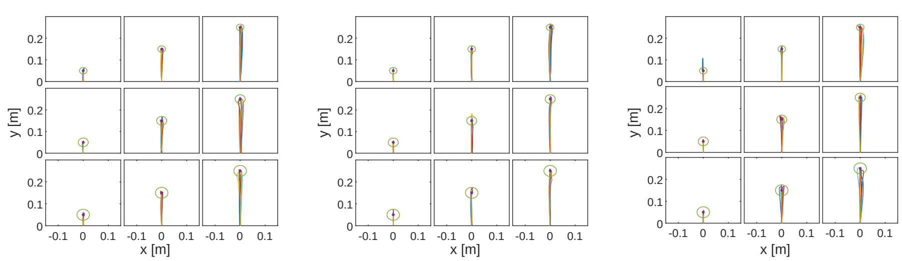
Fig. 2. Simple graphic user interface, showing the starting point (black), target point (red) and the controlled point (white) in real time.

3.2 Experimental protocol

Subjects stood in front of a screen, holding the handle of the haptic interface as shown in Fig. 1. To create a reaching task on a 2D plane, the z-axis of the haptic interface was constrained to a static position, which was determined so that the angle between the subject's arm and forearm was 90deg in the starting position. The x-axis and y-axis movement was also constrained so as to avoid singularities and object collisions.

The experimental session began when the moving point on the GUI reached its starting position. When the moving point was in its starting position a random target appeared on the screen. The subjects were instructed to reach this target as fast as possible and stay inside the target for at least half a second. Note that by staying in the target for a certain amount of time, we prevented the subjects from simply running over the target without aiming for it. After the target was reached the subjects had to return to the starting position. The reaching task was repeated 90 times. This equals to 10 cycles in which the same 9 targets were used in random order.

3.3 Results



(a) (b) (c)

Fig. 3. Displacement trajectories of the controlled point from starting position to the target (a) and (b) for individual subjects. (c) for subjects in collaboration. Each graph represents one out of nine targets, sorted from left to right by their distance and from first to last row by their size.

In Fig. 3 we can see the trajectories for each target and its cycles, where Fig. 3a and Fig. 3b show trajectories of subjects performing the task individually and Fig. 3c shows trajectories of subjects in collaboration. Comparing the trajectories of individual tasks and collaboration tasks, we can see that there is no distinct difference between them.

To understand the performance of our preliminary subjects we created Fitts' law models for both individual subjects and for subjects in collaboration, shown in Fig. 4. The essential feature of the Fitts' law model is to determine the speed-accuracy trade-off based on the time required to reach the target T. As a measure of human performance Fitts proposed a metric called index of performance or IP, which is described as

$$IP = \frac{ID}{MT}, \tag{9}$$

where MT is the measured movement time and ID is the index of difficulty, which has several formats in literature as seen in [2],[13]. Here, we used the Shannon formulation, defined as

$$ID = \log_2 \left(\frac{D}{W} + 1 \right) \tag{10}$$

Here, D is the distance of the target and W the width of the target.

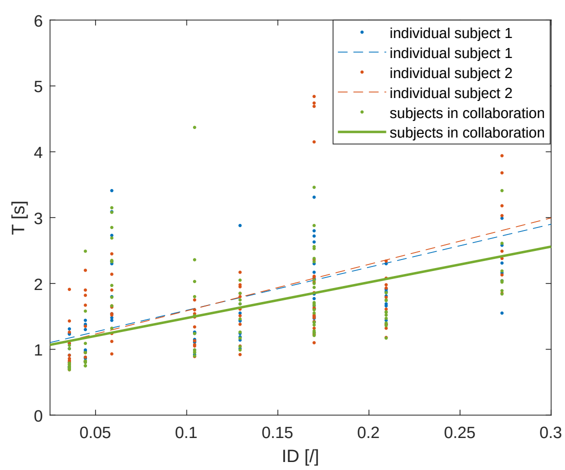


Fig. 4. Fitts' law models for individual subjects and subjects in collaboration, where dots represent measured data for 9 target in each cycle and the linear curves represent the Fitts' law models.

By comparing Fitts law models of individual subjects and subjects in collaboration, seen in Fig. 4, we notice that the Fitts' law model improves when the subjects are collaborating. Note that the movement time is similar between all models at the lower values of ID, with the change being more noticeable when the ID increases. This confirms the results found in the previously mentioned study by G. Ganesh et al. [3]. From the Fitts' law models for individual subjects we can also see, that subject 1 performs better when the ID of the target is higher, while subject 2 performs better when the ID of the target is lower. This can be seen from the difference in movement time between subjects.

4 Discussion

The aim of this work was to develop a novel haptic interface using a dual-arm robot for future use in studies on human-human and human-robot interactions. The key novelty is in the use of a virtual dynamic model to convert a classic redundant robot into a haptic interface. With this virtual model we were able to couple two robot arms to create a rigid body model, where forces applied to any end-effector directly influence the movement of both robot arms. This allows us to effectively study human-human interaction when preforming simple reaching tasks like moving a table or a pipe as seen in [6].

We assessed the performance of the proposed interface by conducting a preliminary evaluation of a human-human interaction. The subjects' task was to perform a simple 2D reaching task, first independently and then in collaboration with each other. We monitored the displacement trajectories of the controlled point displayed on the screen, as well as the time it took for the point to reach the different targets. We discovered that there is no significant difference in the displacement trajectories between the individual and collaborative experiment. This can be expected as the goal through all three experiments stayed the same. It also shows that the developed haptic interface does not interfere negatively with the natural movement of the subjects.

By using the Fitts' law model to analyse the performance of the subjects, we have shown that the results are in compliance with the Fitts' law described in [2], i.e. the larger and closer targets were, the easier it was for the subjects to reach them, therefore the movement times were shorter and the reaching tasks were completed faster. When comparing the Fitts' law model of subjects in collaboration with the individual models, we have shown that subjects' performance in collaboration was overall better than when performing the same tasks independently. This coincides with the results published in [3], stating that an individual performs better when collaborating with a partner even if their partner by themselves performs worse than them. Moreover, when analysing Fitts' law models of individual subjects, we have discovered that one individual's performance is better when reaching targets with lower ID, while the other individual's performance is better when reaching targets with higher ID. This could be due to the former individual being better at reacting, while the latter individual exceeding at aiming, as to reach a smaller target faster, more precision is needed than to reach a larger target.

The study presented in this paper provides a clear indication that the proposed control method can be efficiently used for studies on human-human and later on human-robot interaction. However, there are some limitations of this study. The evaluation was a preliminary one, done using only one experimental setup and one pair of subjects. The reaching task was also a simple one, the haptic interface having its movement constrained to two DOFs, with the target's position changing in only one DOF. Therefore in our future work, we are planning to conduct further experiments on more subjects to be able to statistically evaluate the proposed control method's performance. Furthermore, we are planning to use the developed control method to perform additional studies on human-human interactions, using new study cases.

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