Investigation of Dynamic Behavioural Characteristics of Human-Human Interaction in an Object Handover Task

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Abstract

An important aspect of robotics research is in the area of human-robot interaction (HRI), which addresses the issue of cooperation between a human and a robot to allow tasks to be shared in a safe and reliable manner. This paper demonstrates the evaluation of the human dynamic response based on the McRuer crossover model while undertaking one degree of freedom (DOF) human-human interaction (HHI) object handover. The human behavioural characteristics estimated will subsequently be used to establish a framework for a robotic behaviour-based approach in human-robot interaction (HRI).

A set of one DOF HHI experiments have been carried out based on pilot study recommendations, in which the effective test sample size, number of trials and testing sequence for the large-scale tests were statistically established. In the object handover tests, the handler was required to dexterously pass an object to the receiver in a timely and natural manner. The test results present that the human dynamic model appropriately estimated reported to be in effective matching with the real measurement data, where the best-fit percentages of human interactive profiles are almost 100%. According to the McRuer crossover model, the overall results can be concluded that the average reaction time of the human responses is 0.16s with a standard deviation of 0.01s, which agreed with McRuer [1] that the human perceptual reaction time is in the range 0.1-0.2s. The coefficients of lead time (T_z) and lag time (T_p) are between 0.00-0.01s and 0.00-0.02s respectively. A loop gain (K_H) increases when the object baton is transferred with a faster response and also associated with a higher interactive force occurring between the both participants whilst performing the interactive task.

Keywords : Human-human interaction (HHI) : Human-robot interaction (HRI) : McRuer crossover model

1. Introduction

Industrial robots are typically programmed by operators to execute a sequence of predefined functions. Although early industrial robots were not developed to interact with humans directly, the next generation of smart robots will be designed to further increase flexibility and to share their workspaces with humans in aiming for product improvement. Human-robot interaction (HRI) has become the crucial aspect when robots have been used for collaboration with humans in industrial applications, due to the requirements of technological feasibility and productivity improvements in terms of quality, accuracy reliability and flexibility. Interest in human-robot interaction has tended to increase significantly.

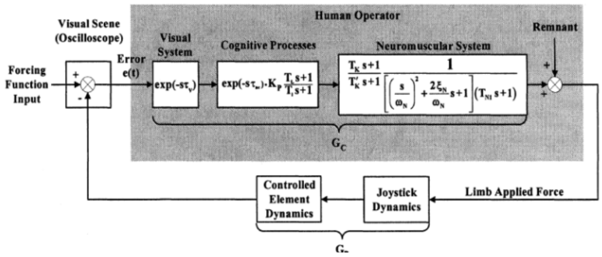

Fig. 1 General architecture of the human operator [8]

Researchers [1-3] stated that understanding the principle of human haptic interaction when two humans work together in a joint effort to complete a shared task is crucial in designing an effective human-robot interactive system. Therefore the aim of this research addresses issues related to investigate the dynamic behavioural characteristics of human-human interaction in an object handover task, which will be subsequently used to develop an appropriate set of behaviours for a human-robot interaction (HRI) control strategy.

2. Dynamic Model of the Human Operator in Human-Machine Interaction

A human-machine system is collaboration of humans and machines to safely and effectively accomplish their coordinated goals. The Human operator plays an important role as a good decision maker since he/she is very good at detecting, identifying and responding to events in a timely manner. Much of the relevant human operator modelling research has been concerned the description of human-machine interaction based on the ability of an individual human operator.

Arata [4] analyzed a human control model, which is useful for design, simulation and evaluation of human-machine interaction. Fitts [5] explained human performance in terms of information transmission. His efforts led to guidelines for instrument panel layouts and other design issues. Zhihao et al. [6] and Trujillo et al. [7] have considered the human abilities, which contribute to successful flying skills in studies aimed at developing pilot tests to enhance training effectiveness.

In principle the adaptive and learning capabilities of the human allow modification of the effective system structure because he/she has after architectural, learning and adaptation phases in order to achieve an effectively similar state. Therefore, in the 1960s, the studies of McRuer et al. [8] evaluated a human characteristics model based on dynamic response in human-machine interaction. The general perceptual control architecture of the major human pathways is described as precognitive, pursuit and compensatory modes.

The McRuer crossover model was based on a combination of sensing, computation and actuating systems, whereas the human operator model was defined as a set of linear differential equations. Nevertheless, a noise term, namely the ‘remnant’ which could possibly be introduced by human non-linear behaviour, muscle tremors and variations in phase lag, is also added to the crossover function in order to take into account variations in the performance of individual humans.

According to a general architecture of major human pathways, the human perceptual control can be divided into precognitive, pursuit and compensatory modes [8]. Fig.1 shows the McRuer crossover model, in which the operator can be illustrated as a linear descriptive function. This model relates to visual, cognitive and neuromuscular systems along with a remnant representing time variation, noise and the non-linear behaviour of the human. Therefore the model can be considered to be a quasi-linear equation.

In the crossover model proposed by McRuer [8] it is assumed that a human operator can adapt his/her behaviour to the overall human-machine plant characteristics and behave as a ‘good servo’ or, in other words, demonstrate good stability and response characteristics. Thus the McRuer crossover region transfer function of the system (G_0) can be expressed as:

$$G_0(S) = G_h(s)G_p(s) = \frac{(\omega_C)e^{-\tau_d S}}{S} \quad (1)$$

where, G_h is a human transfer function as a linear feedback controller, G_p is a machine or plant transfer function, τ_d is reaction time delay of the human, and ω_c is crossover frequency.

The extended crossover model in Eq. 2 has been proposed to accommodate a residual phase lag which was not included in the original crossover model [8]. Here, there are four parameters in the human-machine control model made up of K_H, τ_d, T_z and T_p representing the human muscle gain or loop gain, operator reaction time, the lead and lag coefficients respectively. These components are able to be adjusted according to operator behaviour whilst performing different tasks.

$$G_H(s) = \frac{F(S)}{E(S)} = \frac{(\mathrm{K_H})(T_z S+1)(e^{-\tau_d S})}{(T_p S+1)} \quad (2)$$

3. Pilot Study Design for One DOF HHI

A pilot study is a small experiment in which test results are collected and statistically analysed prior to carrying out an appropriate set of large-scale experiments. This technique is often used in engineering experiments to optimize and conduct proper full-scale experiments along with attempting to reduce costs and avoid wasting time. The pilot study objectives can be defined as:

1) To determine the number of participants required in the full-scale study.
2) To choose the number of trials to be used in the main study.
3) To investigate the order/sequence of tasks.

As suggested by Keppel [9], an acceptable significance level (α) for a scientific experiment is recommended at 0.05 or the 95% confidence interval; therefore, this recommendation was applied throughout the pilot study.

According to the pilot study, four pairs of human participants were randomly selected to complete the object transfer tasks, and they were assigned to undertake five tests each with different sequences of transfer velocities. In summary, the HHI handover experiments are expected to be as follows:

- Based on the power analysis method [9], at least 18 paired participants should be adopted in the main study to ensure the test results are statistically significant.
- According to results from the t-test analysis, the participants will be required to become familiar with the test rig with no less than 2 repetition sets of five different transfer points [10].
- Analysis of variance (ANOVA) test results presented that the test sequence had no statistically significant effects; however, in the real experiments, Experimental Design Generator and Randomiser (EDGAR) technique was also used to generate a random order of experimental tests in order to avoid the effects of human learning.

4. A One DOF HHI Object Handover Task

It is crucial to understand the kinematics and dynamics of human-human handover behaviour in order to design and develop an appropriate set of force and position control strategies for robust, behaviour-based, human-robot interaction (HRI). Thus a set of human-human object handover tests has been undertaken to investigate how the handler and receiver behave whilst performing a single DOF human-human handover task, similar to passing the baton in a relay race. McRuer crossover model, which is effectively used to predict optimized human behavioural characteristics under several different conditions when executing the cooperative tasks, was considerably carried out.

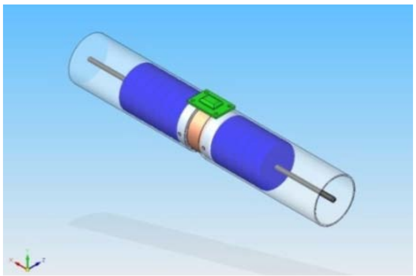

Fig. 2 Design of a one DOF HHI handover baton

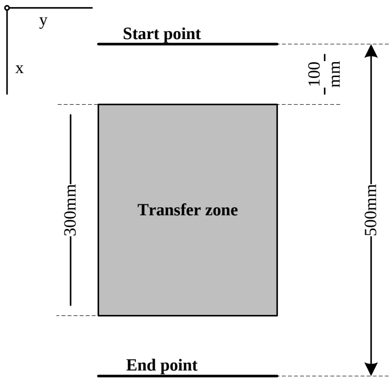

Fig. 3 The workspace of the human-human handover

Before starting the tests, each participant was asked to perform the assigned tests to the best of their ability, without twisting or bending the object. After understanding the HHI dynamic responses, it will be implemented on a robot behavioural control system which enables a robot manipulator arm to interact with a human to facilitate the dextrous transfer of objects in a safe and speedy manner.

4.1 Design of One DOF Handover Baton

The preliminary requirements were defined as the equipment should facilitate the accomplishment of the characterization of the haptic human dynamic interaction. The object comprises an ATI mini40 F/T sensor coupled by cylindrical batons 40mm in diameter and 150mm in length, with a total mass 0.22kg as shown in Fig. 2. A set of masses added can be to increase the load capacity of 0.2, 0.6 and 1.0kg in order to change the moment of inertia of the experimental device.

Whilst executing the interactive task, the interactive forces f_x, f_y and f_z were measured and collected in real-time every 4ms (250) using a ATI mini40 force/torque sensor. The ranges of the force and torque measurements of the ATI sensor are ±80N and ±2Nm with 0.02N and 0.00025Nm resolutions, respectively. In addition a DE-ACCM accelerometer was used to estimate the velocity of the object by integrating an output signal from the sensor.

The sensors (a DE-ACCM accelerometer and an ATI mini40F/T sensor) were connected to a PCI based data acquisition board and an interface power supply (IFPS) box using electrically shielded and twisted transducer cables, The QNX Neutrino real-time operating system v6.4.0 supporting the implementation of the multi-tasking system was adopted to communicate with a power DAQ PCI board, PDL-ME-50 lab series. The PDL-ME DAQ card furnishes six channels of analog inputs and offers the precise quantification of the strain gauge signals transmitted from the IFPS box and the acceleration data.

4.2 Test Procedure for One DOF HHI Handover

As recommended from the pilot study, 18 pairs of participants were required to perform two repetition sets of five object handover tasks. Two human participants were randomly selected to perform the one DOF human-human object handover task at three different conditions, i.e. 10, 50 and 100mm/s. The test was initially assumed that the handler and receiver are working at the different speed platforms, in which the velocity in the object transfer process has to accelerate because the velocity of receiver's line speed (V_d) is twice as much as that of handler ($V_d/2$).

In sending phase, the handler was first instructed to transfer the object to the receiver at the fixed velocity (5, 25 and 50mm/s). When the object had arrived at the interactive zone, it was passed to the receiver similar to passing the baton in a relay race, and then manipulated towards the end point at the demanded velocities (10, 50 and 100mm/s). The workspace of the human-human handover task can be shown in Fig. 3.

5. Estimation of Human Behaviour based on the Extended Crossover Model

This study provides an understanding of the human dynamic response in object handover tasks. This section presents the investigation of the relationship of the two influential variables including mass added and desired transfer speeds affecting the human forces applied to the object handover system and the estimation of the human dynamic response based on McRuer crossover model.

The human force profiles generated here are related to how fast the object is transferred, i.e. the faster the object is moved, the narrower the force profile, and thus to effectively study the effects of the relevant parameters on the human response, the human force measured during performing the HHI task was required to be normalized. The lateral force shapes and object velocity profiles were first normalized based on the average completion time of each task before further analysis.

The results present how the handler and receiver regulate their interactive force and how long the object handover process takes as a function of velocity and added mass of the baton. The findings show the characteristics of the human handler and receiver whilst performing the human-human handover task of several demanded velocities of 10, 50 and 100mm/s and various object total masses of 0.42, 0.82 and 1.22kg.

5.1 Estimation of Human Reaction Time Delay

To determine the unknown parameters $(K_H, \tau_d, T_z$ and $T_p)$ influenced by the actual system's inputs and outputs, a preliminary test was initially conducted to measure operator reaction time (τ_d) using a visual indicator to stimulate the response. An LED indicator was used to enable the participants to push the button as soon as possible; in the meantime LabVIEW Timer0 was started. Once the human pressed the stop button, the LED and Timer0 were simultaneously deactivated, and then the information was captured in real-time using a LabVIEW virtual interface associating with a National Instrument Data Acquisition Card (DAQ USB6211)

From the test results, the mean human reaction time was approximately 0.16s with a corresponding standard deviation of 0.01s, and it was in agreement with those of McRuer [8], in which the values of the human perceptual reaction time were in the range of 0.13 to 0.20s. Consequently, this reaction time delay of 0.16s was applied to strategically estimate the remaining McRuer crossover parameters, i.e. gain K_H, and coefficients of lead T_z and lag T_p, which were identified using the Prediction Error Method (PEM) in the Matlab Identification ToolboxTM. The PEM technique is suitable for use in system process behaviour based upon the basic type of model. Model validation was automatically utilized in the final step of system identification in order to provide a validation of the quality of the simulation model.

Table 1 Estimation of McRuer crossover parameters

	Demaned Velocity (mm/s)	Maximum interactive force (N)	Transfer Time (s)	Muscle gain (K_H)	Reaction time delay (τ_d)	Coeficient of lag (T_p)	Coeficient of lead (T_z)	Fit (%)
Added mass 0.2kg	10	0.85	0.54	0.04	0.16	0.01	0.00	100
	50	1.37	0.41	0.06	0.16	0.01	0.01	100
	100	2.32	0.39	0.45	0.16	0.00	0.01	100
Added mass 0.6kg	10	1.46	0.55	0.06	0.16	0.01	0.01	100
	50	2.43	0.43	0.43	0.16	0.01	0.01	100
	100	2.79	0.38	0.51	0.16	0.01	0.01	100
Added mass 1.0kg	10	2.26	0.52	0.17	0.16	0.01	0.01	100
	50	3.32	0.39	0.79	0.16	0.02	0.00	100
	100	3.62	0.32	2.09	0.16	0.01	0.01	100

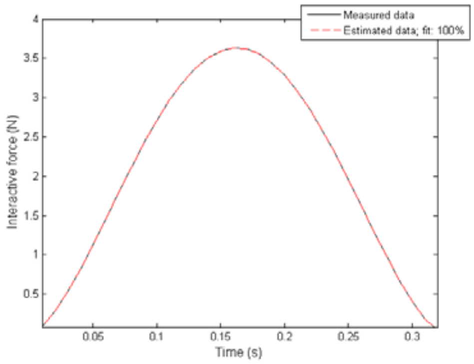

Fig. 4 Comparison results between actual and estimated human interactive force

5.2 Estimation of the Extended Crossover Model

The extended McRuer crossover algorithms were successfully estimated using the Matlab PEM technique. By considering human responses, all estimated models have been summarised in Table 1, in which the results agreed with McRuer [8]. The average reaction time was 0.16s with a standard deviation of 0.01s; the human perceptual reaction time is in the range 0.1-0.2s. The coefficients of lead time (T_z) and lag time (T_p) are between 0.00-0.01s and 0.00-0.02s respectively. For example, one of the test results (added mass: 1kg and demanded velocity: 100mm/s) is can be shown in Fig. 4.

Loop gain (K_H) is proportional to the interactive force between the handler and receiver, and object transfer velocity. In other words, the human muscle gain increases, when the object is passed with a faster reaction. In addition, K_H is associated with the masses added to the handover baton.

In summary, the results indicate that the overall transfer time in the human-human handover task mainly depends on the transfer speed required in the handover process. It can be said that the faster the object has been moved during the task, subsequently a faster transfer time will be achieved. Additionally the influence of the transfer speed rate and the weight of the object are directly proportional to the maximum force applied to the object.

Furthermore, the model validation shows that the percentage of best fit is almost 100%, which is much higher than the normally acceptable percentage of model fitting at 80% of best fit [11].

6. Conclusions

This work presents an outline of HHI to establish the conceptual design guidelines for a human-robot interactive behavioural strategy. It addresses the extended McRuer crossover model to identify the human responses in the object handover tasks.

The McRuer model parameters were effectively estimated using the Matlab Identification Toolbox – PEM technique. All results calculated from different of masses added and demanded transfer velocities were summarised in Table 1.

In summary, it can be concluded that the average reaction time of the human responses is around 0.16s, which agreed with McRuer [1]. The coefficients of lead time (T_z) and lag time (T_p) are between 0.00-0.01s and 0.00-0.02s respectively. A loop gain (K_H) increases when the object baton is transferred with a faster response and also associated with a higher interactive force occurring between the both participants whilst performing the interactive task. Moreover, according to the model validation, the percentages of best fit are almost 100%, which much more than the acceptance percentage of the model fitting at 80% of best fit. Consequently, the estimated dynamic models are effectively acceptable models.

7. References

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