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Prediction of Interactive force in Human-Human Object Handover using Box-Behnken Design of Experiments

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Abstract

An appropriate set of behaviour-based strategies for human-robot interactive (HRI) control can be designed and developed by first understanding kinematics and dynamics of human behavioural characteristics in an effective human-human interactive (HHI) task. To achieve this goal, a real-world human-human object handover task where the handler is able to dexterously pass an object to the receiver in a timely and natural manner in a 3D workspace has been established using a Box-Behnken design of experiments. The profiles of human interactive forces were measured as a function of time under varying baton mass and transfer velocity conditions. Response Surface Methodology (RSM) was applied to mathematically model the physical relationship between the dependent variables (object mass and transfer rate) affecting the human forces applied to the system. By applying Analysis of Variance (ANOVA) technique to statistically evaluate the relationship as mentioned, the test results obtained have confirmed that at least one of the input variables significantly affected the dependent output at the 95% confidence interval. The computed number of R^2 is 0.996, which means that 99.6% of the surface roughness parameter (or predicted force) estimation is meaningfully related to the input variable parameters. Additionally, the adjusted R^2 value (0.993) indicates the second-order polynomial model is highly reliable, in which Mean Absolute Errors (MAE) is approximately 4.8%. Therefore, the prediction model proposed is assured to be confirmed the appropriateness of the equation and highly reliable.

***Keywords**:* Human-human interaction (HHI); Human-robot interaction (HRI); Box-Behnken design; Analysis of variance (ANOVA)

1. Introduction

One of the important aspects of robotics research is in the area of human-robot interaction (HRI), which addresses the issue related to the cooperation between a human and a robot while sharing their workspace in aiming for product improvement in a safe and reliable manner. Appropriate behavioural strategies implemented for human-robot interactive control can be successfully developed by first understanding the principle of human haptic interaction when two humans work together in a joint effort to complete a shared task. This development permits an ‘intelligent’ robot manipulator configured with the capability of generating natural and synchronized responses with a human partner. Therefore, to achieve the above goal, a set of substantive HHI object handover experiments were optimally designed using response surface methodology (RSM) in order to evaluate the human dynamic response throughout the range of interest, where the handler passes a baton object to the receiver along a constrained horizontal path.

2. Response Surface Methodology (RSM)

Response Surface Methodology is a mathematical statistical technique used to establish an approximation model representing the relationship between several explanatory variables and one or more response variables. A crucial property of the RSM technique is to provide a good approach to prediction across the whole region of interest. Researchers have suggested Box-Behnken design [1-2], which is a type of RSM. Box and Hunter [1] suggested the term rotatable which means that the predicted variance is the same for every point based on its distance from the centre point created.

An example of this is where the variance of predicted response is the same for all points located on spheres. Box-Behnken, is also efficiently utilized for few variable factors with regard to gaining maximum amount of information; it is therefore used in the design of the experimental tests. All of the HHI tests were arranged in which eighteen paired-participants were required. An analysis of variance (ANOVA) is used to statistically evaluate the characteristics of interactive force magnitudes (y) as a function of transfer velocity (x_1) and total mass (x_2) of the baton as shown in the following equation.

$$y = \beta_0 + \sum_{i=1}^{k} \beta_i x_i + \sum_{i=1}^{k} \beta_{ii} {x_i}^2 + \sum_{i<j} \sum \beta_{ij} x_i x_j + \varepsilon \qquad (1)$$

i, j are the process orders varying from 1 to the number of variables,

β_0 is the mean of overall experimental responses,

β_i is the coefficient effecting to the variable x_i,

ε is the error observed in response y.

Consequently, Eq. (1) can be defined based on the two dependent variables x_1 and x_2 in terms of their relationship to the output y (maximum human interactive force).

It is given by:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_{12} x_1 x_2 + \beta_{11} {x_1}^2 + \beta_{22} {x_2}^2 \quad (2)$$

As suggested by Box and Hunter [1], the Box-Behnken technique provides a statistically sufficient amount of complex data while also reducing costs in a timely manner. The design requires three significant levels of each factor which are usually expressed as coded values (-1, 0 and 1 representing low, middle and high levels respectively) as shown in Table 1 and Fig.1. Additionally, Table 3 presents all nine different tasks of the Box-Behnken standard design with the two system variables (including transfer velocity and total mass added to the baton) influencing the interactive force (system output).

Table 1 Box-Behnken design: levels of variables

Factor level	**Value**	***Velocity*** (mm/s) x_1	***Mass*** (kg) x_2
Lower level	-1	10	0.42
Middle level	0	50	0.82
Upper level	1	100	1.22

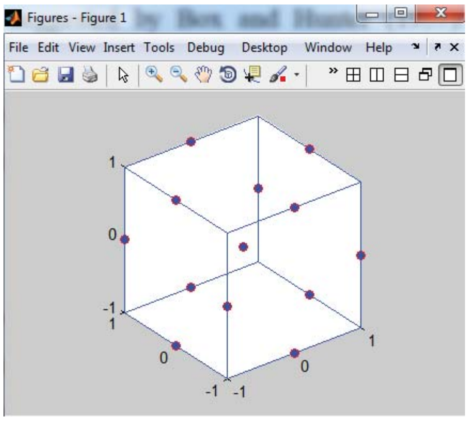

Fig. 1 Box-Behnken design for three factors generated by Matlab

3. Human-Human Object Handover

Extensive researchers [6] have suggested that it is important to design an appropriate experiment, which will provide a statistically sufficient amount of complex data while also reducing costs in a timely manner. A set of human-human interactive tests were therefore carried out using Box-Behnken design to considerably investigate how the handler and receiver behave whilst performing a human-human handover task, similar to passing the baton in a relay race. The tests mimic a real-world object handover task where the handler is able to pass an object to the receiver in a 3D workspace. The kinematics and dynamics of human-human handover behaviour were studied and then used to design and develop an appropriate behavioural control strategy for a robust, behaviour-based, human-robot interaction (HRI).

A designed HHI object handover test comprises an ATI mini40 F/T sensor coupled by cylindrical batons 40mm in diameter and 150mm in length, with a total mass 0.22kg. The handling interactive force applied by the subjects is measured by the F/T sensor and collected in real-time every 4ms (or 250Hz). A DE-ACCM accelerometer was utilized to estimate the velocity of the object by integrating an output signal from this sensor. All signals sensed are connected to a PCI based data acquisition board and an interface power supply (IFPS) box. The QNX Neutrino real-time operating system which supports the multi-tasking system was adopted to communicate with the PCI board, PDL-ME-50 lab series.

The set of experiments as depicted in Fig.2 were successfully undertaken by 18 paired-participants to establish the characteristics of interactive force magnitudes as a function of transfer velocity and mass of the baton. Masses added were 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 in which three different transfer speed conditions, i.e. 10, 50 and 100mm/s were required.

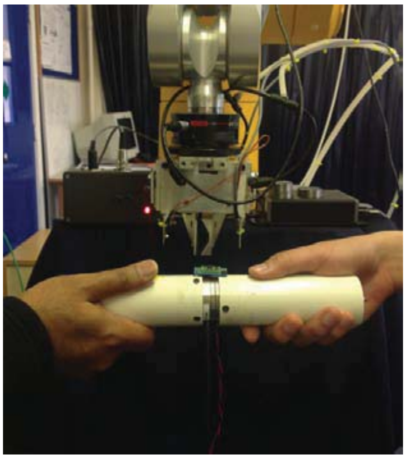

Fig. 2 Design of one DOF HHI handover

4. Test Evaluation of Human-Human Handover

Interactive force profiles present the magnitudes of the interactive forces between the handler and receiver participants against time (t) during the object transfer process. The maximum interactive force (f_{max}) is used to indicate threshold force which represents how much the amount of magnitude of maximum force is taken into account when the handler decides to release the object to be transferred in a natural manner.

The model estimation of the second-order polynomial equation of the response surface can be developed using SPSS [3-5]. The response surface (human interactive force) is characterized using ANOVA for curve fitting and contour plots. In the HHI test, the maximum *handler* forces in each of the Box-Behnken tasks have been used to evaluate the effects of the two influential variables proposed. The analysis of variance of the response variables and regression coefficients using SPSS were carried out under the conditions as follows.

The 95% confidence interval (α = 0.05) was adopted, and the null hypothesis (H_0) and alternative hypothesis (H_1) are as follows:

H_0: There is no statistically significant relationship between the input variables and the dependent output variable

H_1: At least one of the input variables significantly affects the dependent output variable.

The variable coefficients of the second-order polynomial equation can be mathematically estimated along with the proposed initial conditions as follows. It is assumed that the variance of the individual distribution has to be constant for all values of the independent variable, and that the relationship between the dependent variable and each independent variable has to be linear.

Table 2 presents the outputs from SPSS program, and includes the coefficients applied in the second-order polynomial equation and significance values. This equation shown below expresses the relationship between the surface roughness parameter y (human interactive force) and the two variable parameters x_1 and x_2 representing respectively transfer velocity and mass added to the baton.

$$y = 0.029x_1 + 0.970x_2 - 0.00007x_1^2 - 0.997x_2^2 \\ -0.010x_1x_2 - 0.056 \qquad (3)$$

Once, the parameter coefficients in the second-order equation had been computed, the ANOVA method was subsequently used to assess the system response surfaces.

By applying the ANOVA technique to statistically evaluate the relationship between the system variables and surface roughness (human interactive force: y), the test results presented in Table 3 have a significance value of 0.000, which clearly indicates that the hypothesis H_0 has to be rejected and H_1 accepted, i.e. at least one of the input variables or more significantly affected the dependent output at the 95% confidence interval.

Table 2 ANOVA results for the second-order polynomial equation

Coefficients[a]

Model		Unstandardized Coefficients B	Unstandardized Coefficients Std. Error	Standardized Coefficients Beta	t	Sig.
1	(Constant)	-.056	.314		-.179	.859
	velocity	.029	.005	1.161	6.295	.000
	mass	.970	.790	.357	1.228	.223
	x1x2	-.010	.003	-.424	-3.668	.000
	powerX1	-7.382E-005	.000	-.337	-2.039	.045
	powerX2	.997	.473	.605	2.108	.038

Model Summary

Model	R	R Square	Adjusted R Square	Std. Error of the Estimate	Change Statistics R Square Change	Change Statistics F Change
1	.946[a]	.894	.887	.30815	.894	127.116

ANOVA[a]

Model		Sum of Squares	df	Mean Square	F	Sig.
1	Regression	60.351	5	12.070	127.116	.000[b]
	Residual	7.122	75	.095		
	Total	67.472	80			

In order to statistically decide whether an estimated regression model is acceptable or not, the R^2 value is determined which theoretically can have a range from 0 to 1. A suitable correlation between predicted and actual force values will confirm the appropriateness of the equation. In this case, the computed the number of R^2 is 0.996, which means that 99.6% of the surface roughness parameter (y) estimation is meaningfully related to the input variable parameters and the adjusted R^2 value of 0.993 indicates the second-order polynomial model is highly reliable. Fig. 3 shows the contour profile for output estimation of the second-order polynomial model proposed. Table 3 shows a comparison of the predicted dependent variable y, to the actual values, and it can be noted that the maximum, minimum and average absolute errors are 9.4%, 1.4% and 4.8% respectively.

Table 3 Comparison of the predicted and actual force values

Box-Behnken test	Total mass (kg)	Transfer velocity (mm/s)	Actual force (N) Mean	Actual force (N) SD	Estimated force (N)	Error (%)
1	0.42	10	0.85	0.19	0.77	9.41
2		50	1.46	0.28	1.58	8.22
3		100	2.43	0.46	2.28	6.17
4	0.82	10	1.51	0.32	1.60	5.96
5		50	2.42	0.41	2.26	6.61
6		100	2.79	0.58	2.75	1.43
7	1.22	10	2.70	0.56	2.77	2.59
8		50	3.32	0.41	3.27	1.51
9		100	3.63	0.45	3.56	1.93

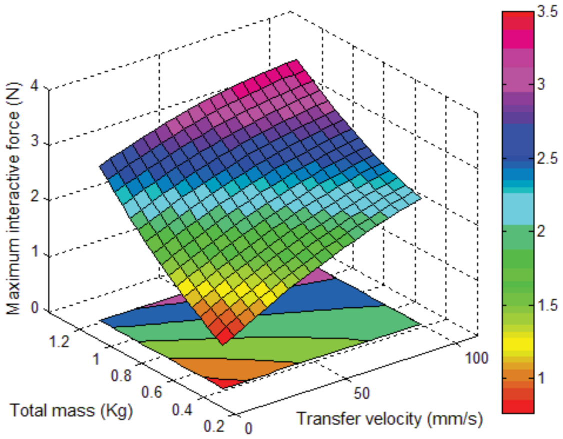

Fig. 3 Contour Profile for output estimation of the second-order polynomial model proposed

5. Conclusion

This paper presents an outline of how the profiles of human interactive forces measured as a function of time under varying baton mass and transfer velocity conditions can be evaluated while performing a real-world human-human object handover task. It extends Response surface methodology (RSM) to identify the human behaviour during passing the baton object to a receiver without any types of communication and to mathematically model the physical relationship between the dependent variables (object mass and transfer rate) affecting the human forces applied to the system.

Based on the measured data along Box-Behnken design, the coefficients of the second-order polynomial equation, involving the independent variables affecting the human forces applied to the system, was conveyed. By applying Analysis of Variance (ANOVA) technique to statistically evaluate the physical relationship, the test results have proved that the effective correlation between the predicted and actual force values confirmed the quality of the calculated mathematical equation. It shows that the proposed equation is assured to be highly reliable and can be effectively used to predict the system outputs across the whole region of interest.

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