Force-Impedance Control for Safe Human-Robot Handovers

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Abstract: One of the crucial challenges to successfully establish a control approach for seamless human-robot object handover is to allow a robot to jointly work together with a human with a safe manner or without the risk of harm or injury by the robot. In this research, Human Support Robot (HSR) has been used in the handover tasks, whose hands were individually attached by a multi-axis force sensor to measure the interactive force acting to the robot end-effector. To adopt the adaptability and robustness in human-robot interaction tasks, robotic force impedance control, which is able to dynamically control the robot motion trajectory and contact force with its environment, has been proposed. The appropriate impedance considered as a mass-spring-damper system has been studied and validated by the object handover testes. The modification of the set of parameters (inertia, damping and stiffness factors) is highly relevant for the cooperative robot behaviour and explained in this paper. Additionally, these results of this study are useful for developing a robotic behaviour-based approach in seamless human-robot handovers in future.

Keywords: Impedance control, Human-robot handovers, Human Support Robot (HSR)

1. Introduction

At present, service robots have become well-known and more seen in homes, shops, companies, hotels, or hospitals, etc. Service robots have been widely developed. One of its most interesting applications is human-robot object handover, which occurs frequently for cooperative robots – i.e. handling an object to a human, delivering a bottle of water to a patient or passing out a mechanic tool to a technician. This is because the robots have good accuracy, and can move at the whole body and end-effector back to their pre-taught positions and directions. However, the robots still need to be improved in terms of a behavioural control system to facilitate the dexterous transfer of objects safely and speedily.

As mentioned in the previous study of Sutiphotinun and his colleagues [1], the paper proposed guidelines in seamless human-robot object handover interaction by understanding kinematically and dynamically how two humans collaborate while performing object handover tasks naturally. Therefore, this paper focuses on the development of a robotic force control system, which will convey the enhancement of the robot's capabilities in terms of their dependability and stability in the object handover tasks.

2. Force Control in Robotic Systems

Robot force control is a fundamental requirement in the achievement of the control of the robot's real-time path in any physical human-robot interaction task. It has been developed in the past three decades, using for example force, torque and visual feedback to operate robots to suitably participate in unstructured environments. Typically, this contact force and torque feedback signals are measured by a multi-axis force/torque sensor before being transferred to the robot controller to generate an updated trajectory of the robot end-effector. This paper emphasizes on the impedance control approach.

The mechanical impedance of a robot end-effector can be adjusted using various relationships between the interactive force and robot position. This method is based upon the control of the difference between the desired and actual position. The force feedback is required to facilitate impedance behaviour [2]. The impedance control approach is that the manipulator control system should be designed not to track a motion trajectory alone but rather to regulate the mechanical impedance (Z_m) of the manipulator. This can be defined by the relationship between the velocity ($\dot{x}$) and the applied external force (F). In general, the robot characteristic is mechanically equivalent to a second-order mass-spring-damper system, with a transfer function. The impedance control can be exposed as:

$$M_d(\ddot{X}-\ddot{X}_d)+B_d(\dot{X}-\dot{X}_d)+K_d(X-X_d)=-F \tag{1}$$

The real-time trajectory of the robot end-effector can be controlled by acceleration as follows:

$$\ddot{X}_r=\ddot{X}_d+M_d{}^{-1}[-F+B_d(\dot{X}-\dot{X}_d)+K_d(X-X_d)] \tag{2}$$

where, M_d is a designed inertia matrix; B_d is a designed damping matrix; K_d is a designed stiffness matrix; $X, X_d\dot{X}, \dot{X}_d, \ddot{X}, \ddot{X}_d$ are vectors of the actual and desired positions of the robot end-effector and their corresponding velocities and accelerations respectively, $\ddot{X}_r$ is defined as a reference acceleration; and finally, F is the force exerted on the robot end-effector. Equation (2) can be depicted as the following figure.

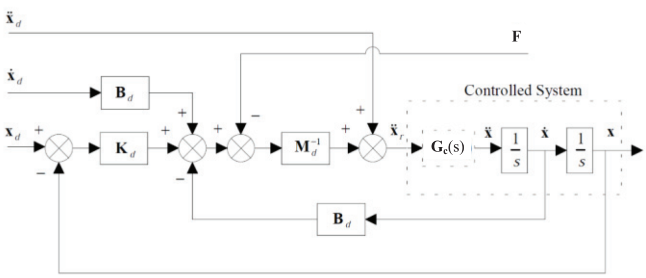

Fig. 1 Block diagram of impedance control scheme [3]

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3. Experiments and Results

3.1 Experiments

This section describes the test based on the robotic impedance control which has been implemented to a Human Support Robot (HSR). The key objective of the study is to evaluate the robotic dynamic response based on the force impedance control while the robot handler interacts with the human receiver in the robot-to-human object handover tasks. The HSR [4] has been developed and considered as a high technology helper, particularly for peoples with disabilities or elderly in their activities of daily living. It has seven degrees of freedom arms with a two-fingered gripper driven by a single motor. Two-type force sensors were fabricated at the robot (end-effector) arm, i.e. a gripping force sensor and a multi-axis force/torque sensor attached at an individual hand wrist. For HSR's head, an 3D-depth sensor was attached to visually track an object position and corresponding velocity. The software architecture was mainly constructed under the Robot Operating System (ROS), in which all sub-programs have to be running synchronously and strictly enforced with a fixed communication rate, as schematically illustrated in Fig.2.

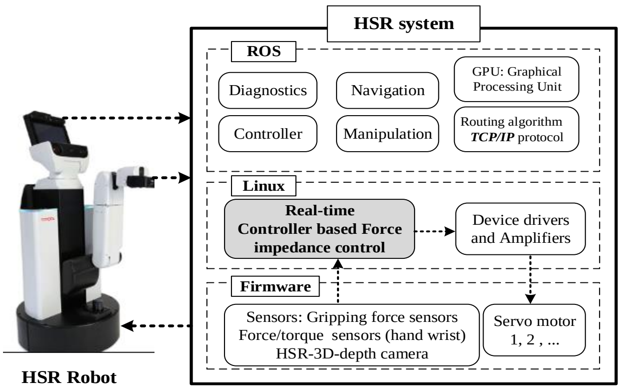

Fig. 2 Schematic diagram of the HSR system

According to the test procedure, a set of participants has undertaken three repetition sets of each handover test under the required variable conditions consisting of spring stiffness (B) and damping factor (K). In the meantime, the maximum interactive force measured by the HSR force/torque sensor is captured. Once the object manipulated by the HSR robot has arrived at a transfer point, the human receiver has to rigidly grasp the object without moving the hand. This is because we want to first evaluate how the robot force control responses if a participant hand cannot move naturally. It is to be noted that the crucial aspect of the human-robot interaction is to protect the human operator (patient) from the risk of harm or injury by the robot's acting force.

3.2 Experimental results

The human-robot object handover tests were successfully carried out by the selected subject group. The results, including maximum forces from the three subsections, namely, (1) damping factor varying system, (2) stiffness varying system and (3) both damping factor and stiffness varying system, are summarised in Table 1.

Table 1 Experimental results

Damping factor (B) varing			Stiffenss (K) varying			B and K varying		
B (NmS/rad)	K (Nm/rad)	F (N)	B (NmS/rad)	K (Nm/rad)	F (N)	B (NmS/rad)	K (Nm/rad)	F (N)
20	6	26.0	2	10	26.5	2	6	14.2
		26.1			26.6			14.1
		26.1			26.7			14.0
10	6	19.7	2	8	26.3	1.5	5	13.4
		20.1			26.3			13.6
		19.9			26.2			13.5
2	6	13.8	2	6	13.8	1	4	12.0
		13.5			13.7			12.1
		13.9			14.1			12.4
1	6	9.1	2	4	13.1	1	3	12.0
		9.2			12.8			11.4
		9.3			12.7			11.7
0	6	9.2	2	2	10.7	1	2	10.9
		8.7			11.2			10.5
		8.8			11.0			10.9

The results present the difference force responses from the force impedance control. This can be assumed that the interactive force can be roughly classified as three main groups: soft, middle and hard categories. According to the (1) and (3) tests, it can be seen that reducing control damping factor gives highly damped behaviour, which is much softer in the robot interactive dynamic response. The outcomes of the (2) and (3) tests show a similar trend as the lower the stiffness values the softer the interactive force response.

4. Conclusion

This paper explains the dynamic behavioural characteristics of the HSR robot based on varying the impedance parameters (damping factor and stiffness parameters) of the proposed force impedance control. In future work, we have to optimize the robotic force impedance control (which is affected by a set of appropriate impedance mass-spring-damper factors) to adopt the adaptability and robustness in human-robot interaction. This will be able to dynamically control the robot motion by the contact force in the dexterous object handover task.

Reference

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