Holding Hands – Guiding Humanoid Walking Using Sensorless Force Control

Jacek Dąbrowski, Polychronis Kondaxakis, and Ville Kyrki

Abstract—**This paper presents a physical human-robot interaction (pHRI) interface, which enables the user to control a walking humanoid robot through physical contact. A human operator guides the robot in parent–child-like behavior by exerting force onto the hand of the robot. In contrast to a conventional approach of pHRI in which force/torque measurements are applied, the proposed solution is based on sensorless force control. Furthermore, we demonstrate an extension to the generic interface by implementing a number of gait control algorithms. This paper also evaluates user-acceptable robot responses while guiding a humanoid robot walking. User opinion on the presented control solution is evaluated through usability testing conducted among prospective users. The obtained results indicate that the developed interfaces present an effective solution to the problem of sensorless guidance of a walking robot.**

I. Introduction

Recently there has been an increased need to study physical human-robot interaction (pHRI) as the communication and cooperation capabilities of robots have expanded. A major focus in pHRI research has been safety [1, 2] where the use of Force/Torque (F/T) and tactile sensors has received lots of attention [3, 4, 5]. Besides safety, recent research has focused on developing ergonomic interfaces. Investigators are studying what characteristics of interfaces are appealing for humans, for example in the context of usability for Programming by Demonstration (PbD) [6].

Guiding a robot by means of a physical contact constitutes another relevant issue in pHRI. People intuitively lead e.g. a child or a visually impaired person by hand in order to direct them to target places. Thus, it is vital to produce a robotic guidance system that provides a natural interface for efficiently guiding a humanoid platform in human-oriented environments. An example of existing research involves leading a nursing assistant robot by holding its hand and changing positions of its arm [7]. Similar investigation was launched towards a force-guided non-holonomic mobile robot. The human user can impact on the robot walk by holding its hand and exerting force onto it [8]. Another important aspect in pHRI involves guiding a walking robot. Some recent work in pHRI investigates the cooperative dance [9]. Here, the user leads the waltz dance by maneuvering a robot through hand control. The robot compensates the force applied in its arms by recreating the steps made by its human counterpart. However, the described guiding system has not been evaluated from a human perspective through usability testing. Generally speaking and to the extent of our knowledge, no earlier studies have been conducted on the applicability and naturalness of such robotic control methods.

This paper presents a novel approach for guiding a walking humanoid robot using pHRI. We propose an interface for pHRI, which is based on sensorless force control. The interaction takes place after the robot straightens out its arm to the vertical position. A human user holds the robot arm and applies external force according to the direction that needs to lead the robot. In turn, the robot compensates this force by adjusting its compliant-walking velocity and directional movement accordingly.

In many available robot platforms there are no force/torque (F/T) sensors. Therefore, another objective is to investigate how force applied to the robot can be detected and interpreted without additional F/T sensors. This paper offers a solution that has been implemented on Aldebaran's NAO humanoid platform. It utilizes information derived from the DC motor, by applying the simplified but yet effective assumption that a DC motor's torque is proportional to its armature current.

The article evaluates the qualities for a physical guiding system that provide the necessary naturality. This is a not straightforward question and to come to a reliable conclusion we evaluated a number of different robot control interfaces on the basis of user studies. By implementing two distinctive controllers we extended the overall structure of the interface. The designed interfaces differ in their performance, applicability and comfortness. Therefore, an objective of this research is to present the usability statistical data of the developed control interfaces.

We begin in Section II by introducing related work regarding force controllers. Section III contains a general overview of the designed interface for pHRI. Section IV presents the structure and implementation of the interface based on the NAO platform. The methodology of controlling the robot's joints is explained along with its application in force control. Section V includes the usability tests for the developed interfaces. Finally, a brief summary with conclusions is presented in Section VI.

II. Related Works

Physical interaction between a human and robot relies, among other things, on the robot's performance and quality. Assessment of these criteria is significantly based on the robot's abilities, such as reaction to external force and adequate force application to a human. Therefore, force

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control is an inseparable element of consideration in order to design and implement an ergonomic interface for pHRI.

The force control algorithm is in charge of regulating either forces between human and robot or/and between the robot and its environment. For instance, some recent research involves the development of a walking robot guidance system for dance-choreography coordination between a human and a robot [9]. The control algorithm determines the dancing movements on the basis of the F/T applied by the user. Different approach of a force-guided robot dance partner is presented in the [10]. The wheeled robot is regulated by the F/T exerted by a human as well as the servo brakes anchored to the wheels.

Most of these algorithms work on the basis of a mathematical model of robot dynamics where information regarding the external force derives from the F/T sensors [11, 12].

Conventional approaches to force regulation, such as impedance control or position-force control, can be found in [11, 12]. Moreover, impedance control aims to regulate the assumed mechanical impedance of a certain object, e.g. a manipulator. In [13] impedance controllers are implemented in order to inspect interaction between a human and robot. First the controller supervises the manipulator motion, which is manually maneuvered by a human operator. The other controller aims to control the force which is applied by the robot to its environment. Publication [8] illustrates another application of the impedance controller, which is utilized for guiding a nonholonomic mobile robot. Another well-known regulation method is admittance control, which is briefly described in [14]. Together with the virtual tool, the admittance regulator is applied in LbD [15]. Investigators conducted research towards enhancing the dynamics of a robot so that maneuvering of the robot would make the impression that the user was operating a real spray gun. Further work on force control using the virtual tool approach can be seen in [6]. The authors studied how particular force regulators affected the usability of LbD from the operator's perspective.

The force control methods as discussed above are based on measurements retrieved from (F/T) sensors. Some robot architectures do not provide access to such sensors [16]. Hence, recent studies concentrating on this dilemma constitute an essential background for the investigation in this paper. One of the sensorless force control methods was elaborated in [17]. The researchers anticipated force by using a motor's armature current as well as the position of the motor shaft. An extension of this examination was presented in the context of object grasping, which was executed by a humanoid robot [18]. The main assumption of the performed work was that the robot would squeeze a certain object featuring some stiffness and located between the robot's arms. Forces generated by the robot's arms as well as the reaction forces that resisted closing the robot's limb were examined in depth. Relationships appearing among these forces and other quantities are discussed. Furthermore, information regarding the motor's current and the distance of the arm were extracted to design the force controllers. The proposed solutions utilize the motor's current to estimate F/T, which is generated by the robot rather than exerted to the robot. Therefore, our research constitutes a unique approach to dealing with this problem.

III. Interface for Physical HRI

The system operation is illustrated in Figure 1. At initialization (lower left in Figure 1), the robot is first moved to an interaction pose shown in Figure 2. The initial angles of arm joints are as follows: Elbow Roll at 3º, Shoulder Pitch at -88º, Shoulder Roll at 4º, Elbow Yaw at 0º and Wrist Yaw at 90ºrespectively.

This pose was chosen so that it allows the user to easily interact with the robot. Further system operations are triggered after a sufficient external force is detected by the arm, indicating that the user is willing to interact with the robot. The operation proceeds then by measuring the pose and motor current of the arm and filtering these signals to remove high-frequency components. The signals are then corrected for bias and the corrected signal is used to estimate the external force. If the external force exceeds a threshold, a controller is used to calculate how to modulate the walking pattern generator used to move the robot.

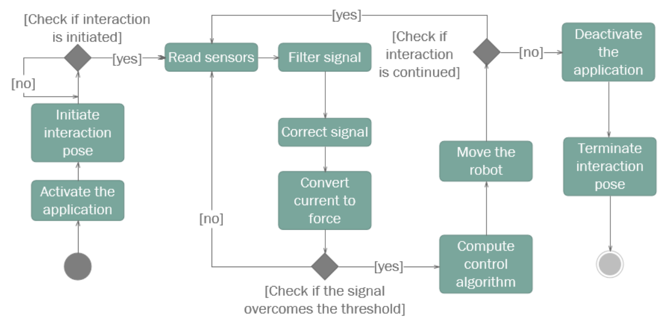

Figure 1. Activity diagram of the designed interface.

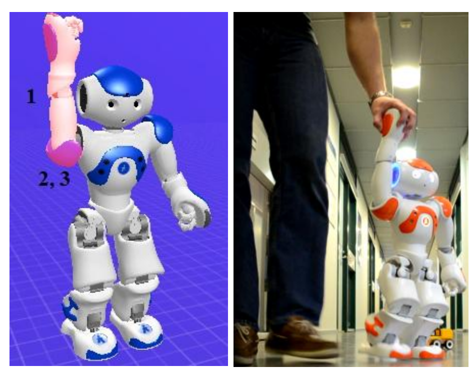

Figure 2. Robot pose for human–robot interaction.

The system model for the proposed interaction system is illustrated in Figure 3. The physical robot is modeled using two components: an arm, where the human applies force, and legs, which move the platform. The control objective is set to maintain a reference position Θ_{ref} with the arm so that if an external force displaces the arm from the reference position, the legs will be used to move the robot to compensate for that. The arm motion control loop outlined with the dashed line in Figure 3 is a basic position controller internal to the NAO robot so that its structure cannot be modified. The only outputs available are the current position which can be used to compute the error of the arm position Θ_{err}, and the motor currents. The amplitude of the error will then affect the motor currents I through the internal controller (Regulator). In addition to the motor torque, the arm is affected by the external (human) force through torque τ_{hum} andthe torque caused by the legs moving the platformτ_{legs}. In the proposed system, the latter torque is controlled through modulating the gait generator parameters so that the error signal in the arm position would be driven to zero. To do this, the dynamics of the arm position controller have been identified and their effect is compensated for by estimating the current I_{pred} in the Corrector so that instantaneous external torque (directly proportional to current I_{corr}) can be used as input for the leg controller. The leg controller uses the torque then to modulate the direction Θ_{legs} and speed υ parameters of the gait controller. This model can be applied to most current humanoids, because only limited measurements (motor position and currents) are needed.

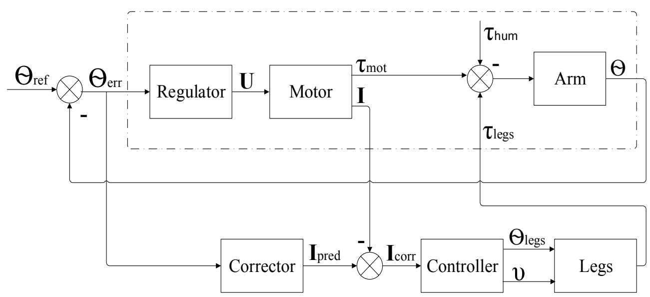

Figure 3. System model.

To demonstrate that the existence of the internal controller breaks the linear relationship between motor current and external torque, Figure 4 shows the position, velocity and motor current for a single arm joint, when either no external force or constant external force is exerted on the arm. Constant force was exerted starting from time 10s and released at time 30s. After the moment of the release, between times 30s and 60s, no external force was present. However, the motor current can be seen to decrease gradually until up to time 39s after which the current remains constant corresponding to the gravity force. This is due to the controller acting to reduce the position error to a hysteresis threshold. The same phenomenon is seen again when external force was exerted starting at 60s and released at 72 s, after which the controller again provides force to reduce the position error. This demonstrates that the current prediction in the Corrector component is necessary.

IV. IMPLEMENTATION

This section describes the implementation of each component within the system.

A. *Positional control*

The positional control sub-system i.e. regulator, motor and arm, have already been implemented by manufacturer. The principle of regulator's working is not facilitated so it is not be detailed here. The arm component corresponds to the chain of joints. Each of the robot's joints is actuated by a high quality brush DC motor described in [16].

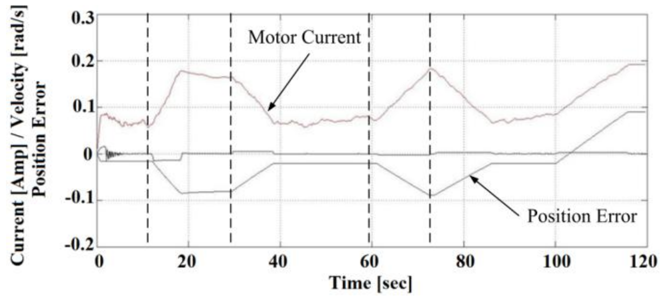

Figure 4. Motor current, position error and velocity under periods of constant external force. The *red line* is the motor current, the *blue line* denotes position error, and the *black line* is the velocity of the robot arm.

B. *Signal filtering and dynamics compensation*

It was noticed that the motor current measurements are affected by high-frequency components not relevant to gait-level control of legs. The current measurements were thus firstly processed by means of low-pass mean filter presentedby the following equation:

$$y_k = \frac{1}{N}\sum_{j=1}^{N} xN \tag{1}$$

The filter extracts and averages N-measurements. Next the result is assigned to the filter's output y_k in the k-moment.

The internal dynamics of the system were compensated for by identifying them. Because DC-motors are used, the model structure was expected to be a second-order transfer function with underdamped poles. The transfer function of this structure can be written

$$G(s) = \frac{K_g(1+T_z s)}{(T_w s)^2+(2T_w s\zeta)+1} \tag{2}$$

where $K_g$is static gain, T_z denotes possible process zero, T_w signifies time constants, and ζ presents the damping parameter. The Prediction Error Minimization method was used to estimate the parameters [19] with data gathered from experiments where a human operator rapidly displaced the robot arm until the end of data acquisition, to provoke an input similar to step response. Experiments confirmed that the model structure describes the real system with 92% accuracy. Experimental comparison to other low-order LTI models confirmed that the chosen model had best fit to measurements. Real system and model responses for a particular input are shown in Figure 5.

To implement the Corrector component, the identified model was firstly converted to a discrete form using first-order-hold[20] and then implemented as a difference equation, illustrated as a block diagram in Figure 6.

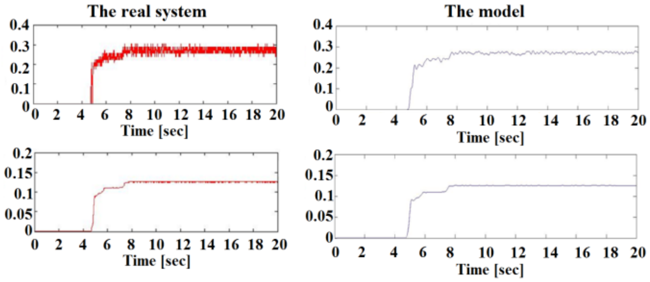

Figure 5. Comparison of model and system responses for a given input

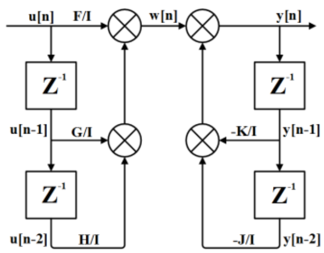

Figure 6. Structure of the implemented corrector

To demonstrate the effect of the Corrector component, Figure 7 shows the measured currents and currents predicted due to the position error by the Corrector for a single joint. Constant external force was exerted on the arm between intervals 21s to 30s, 41s to 45s and 54s to 60s. The corrected current, that is the difference between the measured and predicted values, is shown in Figure 8. It is apparent that correcting for the controller action is needed and that the corrected values are close to equal during intervals with external force, showing that the corrected signal can be used as a basis for force control.

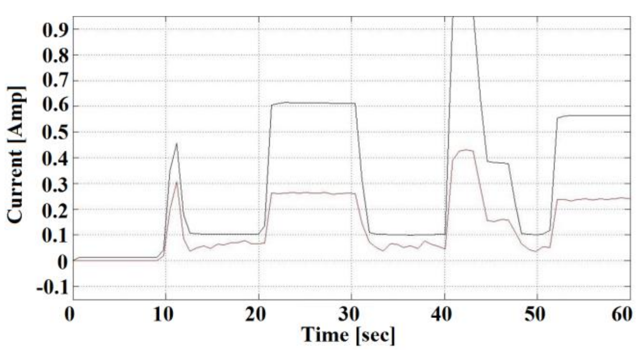

Figure 7. Responses of the corrector and the real system to the same given input

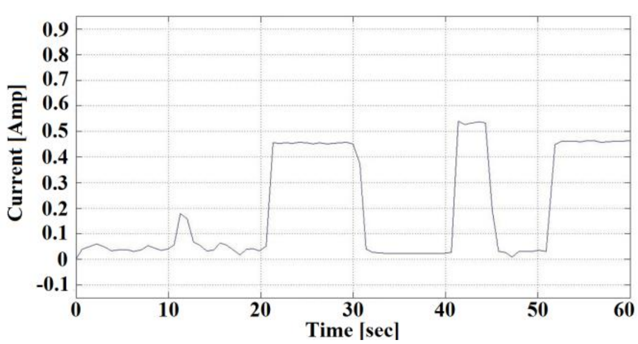

Figure 8. Corrected signal

C. Gait control

The torque applied to the robot arm is estimated based on the motor currents of particular joints, elbow roll, shoulder pitch and shoulder roll, as illustrated in Figure 2. The corrected motor current signals U(t) are used as the input to the controller block which controls the platform motion by controlling gait generator parameters. In this paper, we use the gait generator existing on NAO, where the walking is controlled by step size S, step frequency F, and motion direction. The shoulder roll is used to control the motion direction (turning speed) while the elbow roll and shoulder pitch are used to control the walking speed.

Two approaches are next proposed for the modulation of the gait parameters based on the estimated external torques. These are used to study the effect of different characteristics of the control on the experienced usability. For simplicity, the approaches are called Proportional and PID, although they have other differences besides the controller degree.

Proportional gait controller: The first control algorithm is implemented on the basis of the proportional controller. Thus the control signals, i.e. the velocity and direction of the robot's walk, are proportional to the corresponding motor currents with proportional gain K_f. With the proportional controller, only the frequency of steps is modulated as

$$F = K_f U(t) \quad (3)$$

and the length of steps is kept constant. The turning speed was modulated similarly based on the shoulder roll error.

PID gait controller: The second control algorithm is based on a PID (proportional-integral-derivative) controller. Moreover, in contrast to the first algorithm, it regulates the velocity of the robot's walk by means of adjusting both the frequency and size of the steps. The size of the step is determined by the motor current and a proportional term K_s as

$$S = K_s U(t). \quad (4)$$

The frequency of making steps is controlled by a PID controller

$$F = K_p U(t) + K_i \int_0^t U(t) + K_d \frac{dv}{dt} \quad (5)$$

where K_p, K_i, and K_d denote the proportional, integral and derivative gains, respectively. In addition, integral term limitation was implemented in order to prevent wind-up effect. The turning speed is controlled similar to the proportional controller.

V. Usability Testing for the Designed Interface

The main goal of the conducted test was to provide feedback regarding usability of the designed interfaces. The users specified the performances of each interface and determined any problems obstructing human–robot interaction. Additionally, the testers had to compare the developed solutions and to point to the best solution. Table I presents additional information about the test participants such as gender, age or educational level. All of the users were selected from among students. None of them were familiar with the designed interfaces before the test. As shown in the table, most of the interviewees were men aged 20-24.

TABLE I. USER INFORMATION

Category	Results	
No. of Test Subjects	8	
Sex	Male Female	75% 25%
Age	20 – 24 25 – 33	75% 25%
Educational Level	Bachelor Master	37% 63%

Usability testing was performed at the lobby of TUAS building of Aalto University. Each session lasted approximately 8 minutes. The scenario assumed that the user could freely guide the robot for a specific period of time. The walking trajectory was not predetermined, meaning that a user could guide the robot in any direction. Each interface was evaluated during a 3-minute interview. During the session a user briefly learned how to interact with the robot and then evaluated two interfaces. Next, a test participant filled in an anonymous questionnaire regarding the performed test. Additionally, an interview with the user was conducted afterwards. They evaluated interfaces A and B on the basis of the experience they had obtained during their interaction with the robot. Interface A implemented a proportional controller, whereas interface B was extended by the PID algorithm.

The user could assess each criterion on a scale of 1–5 (where 5 was the highest grade). The mean grades and standard deviations of the corresponding category are presented in Table II.

TABLE II. MEAN GRADES AND STANDARD DEVIATIONS OF PARTICULAR EVALUATION CATEGORIES

	Effectiveness		Accuracy		Naturalness	
	Mean	*Standard Deviation*	*Mean*	*Standard Deviation*	*Mean*	*Standard Deviation*
Interface A	3	0.76	2.75	0.71	2.88	0.99
Interface B	3.63	1.06	2.38	0.52	3.23	0.71

In order to compare the above-mentioned interfaces the users could mark each interface in accordance with three categories: *Effectiveness* denoted the easiness of operating a particular interface, i.e. guiding the robot. Also, it represented the efficiency of performing particular criteria based on time. *Accuracy* embodied the control precision that was provided by a particular interface. During the testing session the user could lead the robot among obstacles and could dynamically change the environment, thus the robot had to react appropriately. The last category evaluated the *naturalness* of each approach. The user estimated how naturally and casually the interaction was conducted.

Finally, the interviewees graded interface A as more accurate than interface B. However, the former featured higher effectiveness and naturalness. Also, most of the test participants marked interface B as the one with the best usability and ergonomics. Nonetheless, some of the results could have been obtained randomly. Therefore, in order to evaluate the received outcomes a statistical hypothesis test was conducted. The main objective was to compare two sets of measurements to assess if their population means differed. Due to the conditions of conducted usability testing, the Wilcoxon signed-rank test was employed [21]. The significance level was chosen as 0.05 (95% confidence interval). The test allowed validating if interfaces A and B were significantly different for the evaluated categories.

Thereby, the distinctions between the interfaces in terms of effectiveness and naturalness were not confirmed by the test. However,the difference in accuracy between interfaces A and B was validated. The users declared their satisfaction regarding both interfaces, although the survey results show a lack of accuracy and naturalness in the developed interfaces. Also, the test participants made other remarks during the verbal consultation. They noticed relevant differences between both interfaces in contrast to the results of the Wilcoxon signed-rank test. According to the test subjects, Interface A was more accurate, but the robot moved too slowly. An advantage of interface A was that it provided more predictable control of the robot's behavior. The other interface was less precise, but the robot moved much faster in response to the larger force applied to its arm. Thus, the testers gave an overall evaluation where interface B provided better naturalness and preferable dynamics of robot movements. It also seems that better capability of the developed interfaces could be achieved by fine-tuning of the implemented regulators.

VI. CONCLUSION

The proposed pHRI guidance system enables a human to control a robot's walk by applying force to the robot's arm in a sensorless manner. Its implementation on a NAO humanoid platform provides a novel solution to the problem. Therefore, the robot compensates the exerted force by adapting its walk according to the external force. The developed system does not require any F/T sensors, but the force applied to the robot's arm is directly estimated from motor current feedback. Experimental results confirmthat the motor current relates to the exerted force but that the effect of the internal position controller needs to be compensated for.

Our results show that without explicit F/T sensors, the effect of the internal robot controllers need to be compensated for. We have proposed a system identification approach which allows this. The approach could be employed in other pHRI tasks beyond guidance.

The naturalness of the proposed system was evaluated using a user study. Statistical hypothesis testing confirmed that a proposed PID controller based approach behaves more naturally compared to a baseline proportional control approach. The testing methodology used in this paper might be employed to evaluate the usefulness of other kinds of interfaces providing interaction between human and robot. For the future, we believe that user studies similar to ones performed in this paper are essential in evaluating pHRI guidance systems.

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