Intention Expression in Stuffed-Toy Robots based on Force Control

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ABSTRACT

A novel stuffed-toy robot that expresses its intentions through the sense of force and touch is proposed. The robot is so soft that one might wish to embrace it. Compliance of the robot can also be determined by holding its hands, similar to newborn babies or small animals.

Core technologies of our robot design include a distributed process multi-rate data-driven force control for the robot's arms and a new force sensor mechanism for detecting external forces acting on the arms. The robot can change its mobility by changing the stiffness of the force control to realize its intention expression.

INTRODUCTION

A future in which we interact with robots on a daily basis is not beyond our reach. In recent years, numerous entertainment robots have been noted for their practical uses that include robot therapy and toy robots.

For interactions with these types of robots, the impression of friendliness is necessary to encourage a feeling of closeness between robots and users. Therefore, many of them are developed as stuffed toys that make people feel comfortable and secure [2]. However, most of these robots utilize hard structures in their moving mechanisms, which are incompatible with the appearance of stuffed-toys. Thus, we assume that these cause users to feel uncomfortable while touching the robots, leading to avoidance.

Harlow's[1] study of baby rhesus monkeys found that they preferred soft touches from their cloth covered mothers over bare wire mothers. This implies that soft contact, such as soft touches, can help to develop affectionate responses, such as friendliness, from the baby monkeys. This is an important factor in developing entertainment robots, namely stuffed-toy robots.

M. Shiina et al. therefore proposed a stuffed robot with a soft mechanism as its movable part. Users can touch and interact with the robot while feeling a sense of softness through tactile sensation. This study suggests that robots with soft mechanisms of interaction can provide good impression to general users over robots with hard mechanisms of interaction.

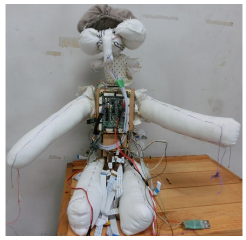
A. Burton[5]'s investigation suggests that pet therapy has a positive effect on patients with neurological diseases and mental illnesses. In places where pets are not allowed, entertainment robots such as PARO[7], can prove to be a good substitute. These robots resemble living creatures whose emotional interactions can help to provide comfort to users. We therefore aim to develop a stuffed robot having its own intentions, much like a living pet that desires close contact with humans, to help us understand its intentions and will; however, to create an interactive expression, force control or impedance control is necessary to change the robot's motion based on the user's input force.

In this paper, we propose a stuffed-toy robot that can express its intention, such as feeling pleased, through force control while maintaining its soft mechanism. The robot is able to sense external forces and provide a feedback force through interactions with its arm, the arm (or hand) being what most people like to touch or shake. Using our approach, the external force that a human applies to the robot's arm will be detected by a special force sensor, and the robot will move its arms accordingly by the force control to express its intentions. As a result, users will be able to understand the stuffed robot's intentions through a handshake interaction with varying amounts of feedback force from its arms.

RELEVANT RESEARCH

In recent years, numerous entertainment robots have been developed, many of which a have similar appearance to that of real creatures capable of interacting with humans. Though they can be built based on different materials and designs,

(a) Stuffed-toy Robot



(b) Robot's Structure

Figure 1: Stuffed-toy Robot

some of these robots resemble cute animals that induce feelings of comfort[2].

The dog robot, AIBO[6], and the seal robot, PARO[7], are good examples of entertainment robots that have cute appearances and can express emotions to interact with users. Although they both yield positive reactions from users, we feel that their hard mechanisms for moving may cause some users to feel uncomfortable while interacting.

Y. Takase et al.[4] studied a stuffed-toy robot made of soft materials, such as clothes and cotton bags. Its movable parts, which included a head, arms, and legs, have soft mechanisms consisting of strings and motors to control their movements during interactions. By using a selective attention model and an external camera, i.e., the Kinect, the robot generated its motion by selecting a point with the highest priority from among users, then reached out to the target point. From the results, the robot received favorable comments from experiments with users.

Based on the stuffed-toy robot[4], we aim to develop interactions that involve the expression of the robot's intentions based on a force control method. Many force control methods could be used here, but most are based on a hard moving mechanism. Therefore, we implemented position-based explicit force control[8], which requires kinematics and precise force sensing that is non-trivial for such soft stuffed mechanism.

PROPOSAL

Requirements

In this paper, the explicit force control method[8] is used to move the robot's hand in proportion to the external force applied that can be described as

$$k(\mathbf{p}_{targ} - \mathbf{p}_{curr}) = \Delta\mathbf{f}, \qquad (1)$$

where $\mathbf{p}_{targ}$ is the target position of the hand, $\mathbf{p}_{curr}$ is the current position of the hand (Fig.4), $\mathbf{f}_{curr}$ is the external force applied to the hand, $\Delta\mathbf{f} \equiv \mathbf{f}_{curr} - \mathbf{f}_{targ}$ is the difference between current force $\mathbf{f}_{curr}$ and target force $\mathbf{f}_{targ}$, and k is a stiffness function for force control. As the mobility of the robot's arm reflects stiffness k, we expect this will affect user impressions on the intentions of the stuffed-toy robot.

We assume hand position $\mathbf{p}$ and actuator position $\mathbf{q}$ (e.g., lengths of pulling strings) are related by $\mathbf{q} = \mathbf{L}(\mathbf{p})$. Then, force control can be defined as

$$\mathbf{q}_{targ} = \mathbf{L}(\mathbf{p}_{curr} + \frac{1}{k}\Delta\mathbf{f}). \qquad (2)$$

Due to the soft fabric and materials, there are two major difficulties in realizing this force control. First, external force $\mathbf{f}$ must be measured without any hard mechanism inside the arm. Second, the relationship between the actuator and the hand position $\mathbf{L}(\mathbf{p})$ is difficult to formulate because the hand movement is caused by a complex deformation of the cotton bag. To solve these difficulties, we propose force sensors at the arm base and multi-rate data-driven force control, each of which is described subsequently.

Force Sensors at the Arm Base

When people grasp a stuffed toy, their hands apply forces to the toy's arm. In our research, the external force acting on the stuffed robot's arm is directly detected to realize force control with two degrees of freedom (DoF). Though the robot's arm consists of three strings, only two strings can be pulled at once to control arm movement. As a result, the hand position can be represented by two angles, as shown in Fig.4. In addition, to maintain the soft motion mechanism of the arm, force sensors are installed at the arm base(Fig.3b). Also, the movement of the arm cannot disturb external force detection, because the force sensor (Fig.3b) is installed between the arm unit and body side. Further, the arm unit may include several actuators (motors), but the force sensor, which consists of an aluminum-elastic body, is hard enough to act as the only connection between the arm unit and body side.

Multi-Rate Data-Driven Force Control

In our previous work, Y. Takase et al.[4] introduced a data-driven position control mechanism for robots made of soft materials. The behavior of a fabric-made mechanism is difficult to formulate, because it is a composition of multiple soft materials, and thus it is difficult to simulate its motion. Every portion of the arm is different in stitching, non-uniformity, and amount of cotton stuffing. Therefore, instead of formulating behavior, we measured hand positions according to several target positions of the actuators. Next, we constructed function $\mathbf{q} = \mathbf{L}(\mathbf{p})$ with the data.

Now, we consider utilizing this data-driven $\mathbf{L}$ for force control. To achieve stable control, the control unit should compute Equation (2) in high frequency (e.g. 2.5 KHz); however, computation and data storage of $\mathbf{L}$ were too much for the microprocessor in the robot's control unit, because it needed to search and interpolate within the measured data. Also, if all computations ran at 2.5 KHz, a lot of power would be consumed.

To solve this problem, we propose a force control based on the differential of $\mathbf{L}$. We define Jacobian matrix of $\mathbf{L}$ as $J_L \equiv \partial\mathbf{L}/\partial\mathbf{p}$. J_L is a function of $\mathbf{p}_{targ}$, and therefore, even with a high frequency force control, a change of J_L is relatively slow. In addition, the displacement is proportionally small, and a linear approximation is also possible. Hence, we formulate the control with J_L and update J_L in low frequency. Details are described below.

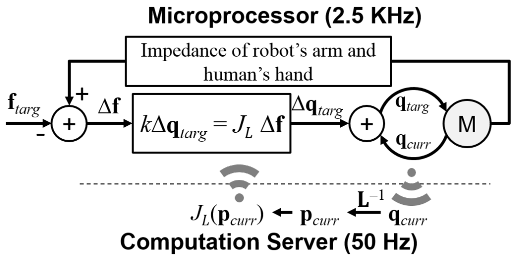


Figure 2: Multi-Rate Force Control

First, we define the difference of target actuator position $\mathbf{q}_{targ}$ and current actuator position $\mathbf{q}_{curr}$ as $\Delta\mathbf{q}_{targ} \equiv \mathbf{q}_{targ} - \mathbf{q}_{curr}$. We therefore describe Equation (2) in the following differential form of $\Delta\mathbf{q}_{targ}$.

$$k\Delta\mathbf{q}_{targ} = J_L \Delta\mathbf{f}. \tag{3}$$

From Equation (3), $\Delta\mathbf{q}_{targ}$ should also be computed in high frequency, because the update period of digital control system causes a time lag on the feedback loop. This time lag can consume the phase margin and thus bring instability to the system.

Fig.2 shows an overview of multi-rate control. Because of low update rate, the computation of Jacobian matrix J_L can be distributed onto an external computation server over a wireless connection. The computation server may not be used in real toys, but the multi-rate control is still required to reduce computational costs.

IMPLEMENTATION

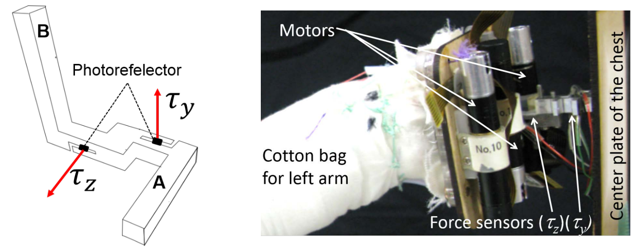
System Structure

The force control works with torques $\boldsymbol{\tau} = (\tau_y, \tau_z)^t$ from the external force input from the force sensors and determines a target length of three strings on one arm, $\mathbf{q} = (L_1, L_2, L_3)^t$. If all three strings were pulled at once to control the movement of the robot's arm, the cotton bags in the arm would shrink and not expand back to their original size; however, by pulling two of the three strings at the same time, the tip of the arm can approximately move on a spherical surface. Thus, we can describe a hand position with spherical coordinate $\mathbf{p} = (\theta, \phi)^t$ in the control system.

Fig.4 shows the definition of the coordinate system of the robot. The origin is located at the center of the root of the robot's arm, whereas $\mathbf{P}_{curr}$ denotes the position of the robot's hand. In addition, r in $\mathbf{P}_{curr}$ is not a constant; it denotes the value of 0.15 m from the length of the cotton bags in the arm while ignoring its change in size.

Force Sensor

Fig.3a illustrates the structure and installation of the force sensor. Two photo-reflectors (SG-105, Kodenshi corp.) that are installed in the slits of two individual Duralmin cases (Fig.3b), can sense the widths of both slits. As the force applied to the arm causes the force sensor to deform, both photo-reflectors can detect the force by the changes in each slit's width. The sensor is located between the arm unit and the body's side, as mentioned above.



(a) Structure (b) Installation

Figure 3: Force Sensor

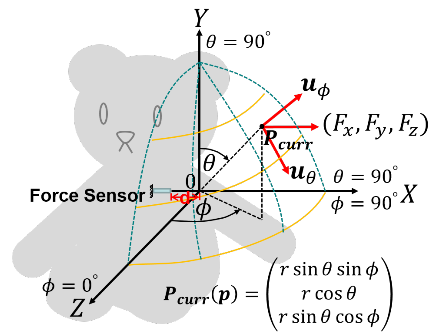


Figure 4: The Coordinates of the Robot's Arm

The external forces can be detected in two DoF and converted into torques. Fig.3a illustrates the two directions of force measurement. The force sensor in part A can measure torque τ_y in the horizontal direction, whereas the force sensor in part B can measure torque τ_z in the vertical direction. Also, in the Cartesian coordinate system of Fig.4, external forces f_ϕ and f_θ can be detected by the force sensor.

Force Sensor Calibration

The microprocessor reads the force sensor value with an analog-to-digital converter (ADC). Next, we need to convert the ADC value to force[N]. In addition, every force sensor has its own individual characteristics. Therefore, we need to determine a force sensor calibration function for each axis of each force sensor.

To build a force sensor calibration function, we measured several pairs of ADC values according to some external force applied. Next, we applied linear regression techniques on the data to obtain the fitted function (e.g., logarithmic function, polynomial function). Finally, we used the fitted function to convert ADC values into their corresponding torques over a range of data, and kept both matching pairs of values as the torque calibration map.

Force Control

Torque Acquisition

The ADC value of the force sensor changes when forces are applied to the arm. Therefore, torque can be obtained by mapping to the corresponding torque in the torque calibration map, as noted above. For example, ADC_1, the horizontal direction value, and ADC_2, the vertical direction value, are mapped to τ_y and τ_z, respectively, the corresponding torques of these two directions.

Force Derivation

Based on the Cartesian coordinate system, we can describe torques in two directions by the relation of the force applied and its position to the pivot as

$$\begin{pmatrix} \tau_y \\ \tau_z \end{pmatrix} = \begin{pmatrix} P_{c_z} & 0 & P_{c_x} - d_y \\ P_{c_y} & P_{c_x} - d_z & 0 \end{pmatrix} \begin{pmatrix} F_x \\ F_y \\ F_z \end{pmatrix}, \quad (4)$$

where P_{c_x}, P_{c_y}, and P_{c_z} are the elements of $\mathbf{P}_{curr}$ (Fig.4), d_y and d_z, which are approximately 0.035 m and 0.01 m, respectively, are the distances from the pivot of the force sensors in the X direction, and $(F_x, F_y, F_z)^t$ is the force applied on the arm in Cartesian coordinates. While ignoring the force in the radius direction, this force can also be described in a basis form based on polar coordinate (Fig.4) as

$$(F_x, F_y, F_z) = f_\theta \mathbf{u}_\theta + f_\phi \mathbf{u}_\phi, \quad (5)$$

where $\mathbf{u}_\theta = (\cos\theta \sin\phi, -\sin\theta, \cos\theta\cos\phi)^t$ and f_θ are the basis vector and force in the θ direction, and $\mathbf{u}_\phi = (\cos\phi, 0, -\sin\phi)^t$ and f_ϕ are the basis vector and force in the ϕ direction. Then, from Equations (4) and (5), we can describe the torque in the y and z directions based on the spherical coordinates, which yields

$$\begin{pmatrix} \tau_y \\ \tau_z \end{pmatrix} = \begin{pmatrix} r\sin\theta - d_y \sin\phi & d_y \cos\theta\cos\phi \\ -r\cos\theta\cos\phi & d_z \sin\theta - r\sin\phi \end{pmatrix} \begin{pmatrix} f_\phi \\ f_\theta \end{pmatrix}. \quad (6)$$

Based on Equation (6), we can finally calculate forces f_ϕ and f_θ from torques.

Length Conversion

From the force control method in Equation (1), we can derive the force as

$$\Delta\mathbf{f} = k(r\Delta\theta\mathbf{u}_\theta + r\sin\theta\Delta\phi\mathbf{u}_\phi), \quad (7)$$

where k is the stiffness of the force control, $\Delta\theta$ and $\Delta\phi$ are the amount of change in angles of θ and ϕ, and r is the length of the arm. In our experiment, we assume $\mathbf{f}_{targ} = 0$, and so, from Equations (5) and (7), we derive the amount of changes in both angles as

$$\Delta\mathbf{p} = \begin{pmatrix} \Delta\theta \\ \Delta\phi \end{pmatrix} = \begin{pmatrix} f_\phi/(kr\sin\theta) \\ f_\theta/(kr) \end{pmatrix}. \quad (8)$$

Next, the amount of change of string lengths can finally be calculated as

$$\Delta\mathbf{q}_{targ} = J_L \Delta\mathbf{p}. \quad (9)$$

In Equation (9), J_L is a Jacobian Matrix based on the hand positions-string lengths map, $\mathbf{L}(\mathbf{p})$, which is made up of the mapping of data between the target lengths of string $\mathbf{q}$ and hand position $\mathbf{p}$. J_L is provided by the computation server in low update-rate and can be calculated by

No.	Pairs of Adjective Words (形容詞句対)	
Q1	Friendly（親しみやすい）	Unfriendly（親しみにくい）
Q2	Peaceful（安心な）	Unpeaceful（不安な）
Q3	Emotional（感情を持つ）	Impassive（感情を持たない）
Q4	Charming（好ましい）	Boring（好ましくない）
Q5	Understandable（心が通じる）	Not understandable（心が通じない）
Q6	Pleased to shake hand（テディベアは喜んで握手している）	Forced to shake hand（いやいや握手している）
Q7	Obedient（従順な）	Obstinate（強情な）

Figure 5: Adjectives for the Force Control Questionnaire

$$J_L = \begin{pmatrix} \frac{L_1(\theta+\Delta\theta,\phi)-L_1(\theta-\Delta\theta,\phi)}{2\Delta\theta} & \frac{L_1(\theta,\phi+\Delta\phi)-L_1(\theta,\phi-\Delta\phi)}{2\Delta\phi} \\ \frac{L_2(\theta+\Delta\theta,\phi)-L_2(\theta-\Delta\theta,\phi)}{2\Delta\theta} & \frac{L_2(\theta,\phi+\Delta\phi)-L_2(\theta,\phi-\Delta\phi)}{2\Delta\phi} \\ \frac{L_3(\theta+\Delta\theta,\phi)-L_3(\theta-\Delta\theta,\phi)}{2\Delta\theta} & \frac{L_3(\theta,\phi+\Delta\phi)-L_3(\theta,\phi-\Delta\phi)}{2\Delta\phi} \end{pmatrix}. \quad (10)$$

According to Equation (10), to obtain J_L, we need to call mapping function $\mathbf{L}(\mathbf{p})$ four times to yield the corresponding $\mathbf{q}$, then use them to calculate the differentials with respect to $\Delta\phi$ and $\Delta\theta$.

EVALUATION

Force Control Experiment

For our research, we designed an experiment to evaluate the results of our work. The purpose of this experiment was to check whether participants change their impression of the robot when the stiffness of force control k is changed. In the experiment, we first asked each participant to use his or her right hand to shake the right hand of the robot, and then answer a questionnaire.

For each participant, these two steps were conducted in two different settings, namely stiffness values equal to 1.5 and 3.9. The order of both settings was random. Generally, the mobility of the robot's hand can be changed by stiffness k. In fact, we found that if k is larger than 3.9, users can barely feel the force control on the hand, while if k is smaller than 1.5, the robot's arm will shake by itself. Due to these reasons, we decided to use k equal to 1.5 and 3.9 for our experiments to see the effect k has on the participants' impression of the robot.

Force Control Questionnaire

The questions in the questionnaire were about user impressions of the robot after shaking hands with it. They were constituted by seven pairs of adjective words, as shown in Fig.5. Every question has five levels of answers that are defined from degree five to one, five being the closest to a positive answer while one is the closest to a negative answer, and three indicates neither a positive nor negative answer. In other words, if the score is higher, it means closer to the positive answer.

Force Control Experimental Results

The participants in our experiment consisted of twenty people, including eight woman and twelve men in their 20s. Fig.6 displays a graph of the results from our experiment according

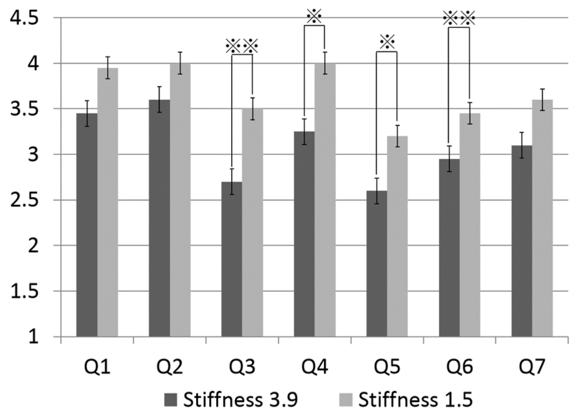


Figure 6: Force Control Experimental Results

to the questionnaires. The graph shows the average score of each question. The average score given a stiffness of 1.5 was higher than that of a stiffness value equal to 3.9.

The Wilcoxon signed-rank test was also applied to analyze questionnaire results. We determined that Q3($Z = -2.1$) and Q6($Z = -1.8$) have less than five percent significant difference; Q4($Z = -2.48$) and Q5($Z = -2.07$) have less than one percent significant difference. Note that Q1($Z = -1.54$), Q2($Z = -1.78$), and Q7($Z = -1.45$) have no significant difference.

Result and Discussion

For Q6($p < .05$), regarding whether the robot is pleased to shake hands with the participant, we found that the participants' impressions could be changed by adjusting k. Q3 'Emotional - Impassive'($p < .05$) and Q5 'Understandable - Not Understandable'($p < .01$) also indicate that the participants' impressions of the robot in human-likeness could be altered by changing k. Also, Q4 'Charming - Boring'($p < .01$) reveals that the participants' attitude toward the robot can be modified by adjusting k.

From the Wilcoxon signed-rank test results, there were three questions without any significant differences. We assume that this is because men and women have different characters. So, when they shook hands with our robot, men preferred a quick handshake as compared to women, who preferred a slower handshake. As a result, when we performed the Wilcoxon signed-rank test only on men's data, there were significant differences from Q1 to Q6.

Different participants had different opinions about Q7 'Obedient-Obstinate.' Some participants guessed the slow movements ($k = 3.9$) as an obedient response, while fast movements ($k = 1.5$) were interpreted as an obstinate impression. Also, other participants thought the opposite; however, almost all participants considered that the robot set with stiffness equal to 1.5 was more active than the robot set with a stiffness value of 3.9.

The impression experiment of the force control indicates that user impressions of the robot could be changed by different stiffness values of k. Hence, it is possible to realize a robot's intentions and expression through force control.

CONCLUSION AND FUTURE

In this paper, we proposed intention expression for a stuffed-toy robot based on force control. We realized a new method of force control for fabric-based stuffed-toy robots. By force control, the stuffed-toy robot could move its soft arms according to external forces by the user. Finally, we confirmed users felt different intentions and impressions in interactions by changing the stiffness of control gain.

In the future, our goal is to realize a heart-touching robot by touch feelings and force sensation. For example, it will be a new medium for pet therapy inside hospitals in which real pets are not allowed. Moreover, the stuffed toy robot can become a robot that people want to live with. It can be a new partner for people of all ages, and will lighten up our daily lives.

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