Towards robotic drinking assistance: Low cost multi-sensor system to limit forces in Human-Robot-Interaction

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ABSTRACT

Assistive robotic manipulators have the potential to support individuals with severe motor impairments at performing activities of daily life. With the help of robotic manipulators, the individuals may eat and drink independently of caregivers. The presented research work focuses on interactive drinking with a cup without a straw. The interaction exposes the user to potential harm due to the direct contact with the robot. In the presented work, a multi-sensor system is outlined, which ensures harmless contact forces between robot and human during an interactive drinking task. Tests on a healthy subject are performed and indicate pain-free interaction with the system. The sensor system is designed to allow the user an intuitive control of the task. The lip pressure is measured at the contact points and will be used in future work to control the tilting angle of the cup, which is grasped by the robot.

CCS CONCEPTS

• **Human-centered computing** → *Collaborative interaction*.

KEYWORDS

Human-Robot-Interaction, HRI, Human Intention Recognition, Robot Nursing, Assistive Robotics

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1 INTRODUCTION

People with severe motor impairments depend on caregivers for fundamental Activities of Daily Life (ADLs). Assistive Robotic Manipulators (ARM) have the potential to support motor impaired individuals at regaining their independence in performing ADLs. Eating, drinking and preparing meals have been shown to be highly prioritized tasks for end-users of ARMs [1].

In recent years, several systems [2] have been developed to aid with ADLs by manipulating objects with an ARM. They can

enhance the capabilities of people with disabilities in work-related tasks [6]. Drinking assistance is often implemented as an object manipulation task where the drink is delivered to the user's face. Direct contact with the face is avoided by drinking from a straw. A more natural way of assistive drinking is achieved in [15] by tilting the cup stepwise while in direct contact with the user's mouth.

Figure 1: Test setup with a healthy subject

The main goal of the presented research work is to further increase the comfort during drinking tasks by using a stepless cup tilting motion in direct contact with the user (See Fig.1). The user will control the tilting angle with their lip pressure. The drinking task will consist of the 4 steps: 1) deliver the cup to the mouth 2) engage contact 3) tilt the cup (drink) 4) retract the cup. The mouth's position is assumed known, for example by using [4]. The task will be implemented on a commercial ARM, the Kinova Jaco [10].

Tilting the cup while it is in contact with the user's face potentially harms the user. Since it is an essential requirement for every Human-Robot Interaction (HRI) to not harm the human, applied forces on the body have to be limited. At the same time, contact losses have to be avoided to prevent spilling of liquid. Both requirements can be met by controlling the applied forces. Therefore, sensor hardware is needed that measures the forces at the lip.

The contribution of the presented paper is a low cost multi-sensor system, consisting of force and distance sensors, that limits interaction forces applied by a drinking cup on the user's mouth. The force sensors are placed at the expected contact points with the mouth to measure the upper and lower lip pressure. These measurements are used to limit the applied forces in a closed loop control. In future work, the force feedback will be used to adapt the tilting angle of the cup to drink the desired amount of liquid. The distance sensors are used to speed up the drinking task. Instead of driving slowly during the whole task, the speed is adapted to the distance. The sensors are connected wirelessly to the controller, which may influence stability due to communication delay.

In section 2, related work is presented. Section 3 shows the general controller structure for safe interaction, whereas section 4 contains the hardware implementation. Tests and results are presented in section 5 and section 6 contains the conclusion.

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2 RELATED WORK

Various systems have been designed to assist people with severe motor impairments with their ADLs. The ASIBOT [8] has a wide variety of end effectors for different tasks such as eating and drinking. The ASIBOT stops when it is in contact with the person or close by. Therefore drinking is only possible with straws. Besides the variety in applications, the robot can also be controlled by different interfaces, that match the physical capabilities of the user.

In [9] objects are detected and grasped automatically. Using gestures, the user chooses an object and where to place it. This allows complex grasping tasks such as drinking from a straw, making a phone call or taking pictures with a single system.

The work [7] uses a common platform for assistive robotics, the PR2 from Willow Garage, to shave a man with tetraplegia. The PR2 holds a mirror and an electric shaver, while the user does the shaving motion with his head. Force sensors in the robot's arm are used to retract the shaver whenever endangering forces occur.

In [15] the robot delivers water in a cup. The user sends commands via a Brain Computer Interface (BCI) to the robot, whereas the robot calculates necessary trajectories. The cup and mouth position are detected with an RGB-D sensor. No force feedback is used, hence the user instructs the cup-tilting in predefined steps. Similarly, in [13] the robot completely plans a feeding task. The user chooses the food with BCI by looking at corresponding flickering LEDs. The mouth is detected with a camera and the feeding is instructed by opening the mouth, instead of using the BCI.

The PR2 robot in [12] is capable of feeding yoghurt to people while adapting to force feedback. One end-effector holds a bowl with yoghurt and the other is equipped with a soft silicon spoon, which reduces the risk of injuries. Force feedback is used to limit the applied forces. A microphone, placed at the end-effector, detects choking noises to retract whenever the trachea is blocked.

The existing systems do not react to user intentions during command execution. This presented research project focuses on increasing the controllability of the drinking task in every step of the execution. Force feedback is used not only to provide safety for the users, but also to control the robot intuitively.

3 VIRTUAL FORCE IMPEDANCE CONTROL

It is required to prevent the HRI system from harming the user. Therefore, the contact and impact forces must be limited during the complete drinking interaction. At the same time, continuous contact is required to prevent spilling of liquid.

The structure of the dynamic system changes when the cup gets in contact with the user. Therefore, the control task is divided into driving (towards the user) mode and user contact mode. To accomplish the safety requirements and to handle the structure change, the virtual force impedance control (see Fig. 2) is used. In both modes, it calculates a velocity to correct the target error reported by the sensors. The controller requires the distance to the mouth and the force at the contact point with the mouth.

In contact mode, the applied force (f) at the contact point is controlled via an impedance controller, which calculates the correcting velocity via $v(f) = \frac{f - f_{target}}{k_f}$ with the constant k_f . f_{target} is set empirically to 0.45 N to sustain the contact, while avoiding painful pressure. A range of 0.35 N to 0.55 N is accepted without any

Figure 2: Impedance controller with virtual and real force

correction to improve the controller's stability around the target value.

In driving mode, distance measurements (d) are used to adapt the speed of the gripper. When engaging contact, the speed has to be minimal to not harm the user. But the larger the distance is, the faster the robot can drive. Therefore, the function $v(d) = \frac{d - d_{target}}{k_d}$ with a constant k_d can be applied to calculate the desired speed v .

$v(d)$ is equivalent to the contact mode function $v(f)$. Thus, force and distance values can be fed to the same impedance controller. This can be seen as interpreting d as the virtual force f_d that pulls the gripper to the mouth. Switching modes can be triggered by a simple threshold on the force measurement. Only the parameters and the input of the controller have to be changed between modes.

4 MULTI-SENSOR SYSTEM

The virtual force impedance control requires the distance to the mouth and the contact force. The values are provided by a multi-sensor system, consisting of the Smart Cup, a stand-alone unit measuring the contact force, and 3 distance sensors at the gripper.

4.1 Smart Cup

The Smart Cup (see Fig. 3) is a feeding cup with 2 Force Sensitive Resistors (FSR) glued to the contact points of the lips. FlexiForce A201 [17] sensors are chosen, since they do not interfere with the drinking process. The front sensor is used to limit the applied forces on the mouth, whereas the back sensor is reserved for future research, dealing with the tilting angle control of the cup.

The feeding cup reduces the risk of spilling liquid. However, the sensors can be attached to other cups. The electronics are placed in a casing at the bottom of the cup. This way the electronics do not obstruct grasping the cup.

The sensor signals are evaluated by a BGM111 [11] on a custom 26x28 mm board, which fits for various cup sizes. The board publishes the force signals via Bluetooth and runs on a 3 V coin cell. As a drawback the wireless connection may fail due to disturbances or power losses. Therefore, connection checks are necessary and implemented. If no new data is available for a predefined time (50 ms - the doubled communication delay) the controller stops the task.

For calibration, different weights from 0-0.1 kg were applied on the force sensors. A linear regression model is used according to the specification [17]. The sensors have biases up to 0.2 N in their measurement range from 0 to 1 N. The FSR are sensitive to

Figure 3: The Smart Cup with force sensors

the pressure distribution on the sensor. The noise variance of the sensors is negligibly low, hence it does not need to be filtered.

4.2 Distance sensors

The gripper is equipped with one distance sensor at the wrist and two distance sensors at the fingers (see Fig. 4). The wrist sensor (Sharp GP2Y0A51SK0F [16]) is placed on a custom designed 3D-printed mounting. The finger sensors (Sharp GP2Y0A41SK0F [16]) are mounted with modelling clay and point at the face when the gripper is closed. The measurement range of the finger sensors is 2-15 cm. Since the wrist sensor is around 10 cm behind the contact point, it is chosen with a higher range of 4-30 cm, losing resolution in contrast to the finger sensors.

Figure 4: Distance sensors at the gripper

Small, low cost, and noisy sensors are used. For noise reduction, the signals are filtered with a mean window. Calculations are carried out by an ESP32 [3] placed at the wrist mounting. The signal is transmitted via Bluetooth to not obstruct the robot's movement by cables. The necessary LiPo-battery is hidden in the mounting.

The distance sensors were calibrated on a doll head as the target. The characteristic of the measurement curve is non-linear, with a higher resolution in close distance. It is approximated with increased weighting on measurements between 0 and 50 mm. In this range biases are below 20 mm. Whereas the finger sensors have negligible noise variance in close distance, the wrist sensor still has heavy noise with σ up to 30 mm due to the larger distance.

5 TEST SETUP AND RESULTS

The test setup starts with the robot holding the Smart Cup (see Fig. 1). All sensor values are received from an additional ESP32 at

the PC and published to the Robot Operating System (ROS) [14] via `rosterial_arduino` [5]. The controller is implemented as a ROS-Node.

The tests were performed on a healthy subject (see Fig. 1). In the current state, the position of the mouth is assumed known. Therefore, the tests start with the gripper pointing at the mouth at approximately 40 cm distance, instead of detecting the mouth's position online. This way, the gripper only needs to drive forward with one dimensional speed to establish contact. The subject was told to hold position until the initial contact was established by the robot. Afterwards, the subject was advised to move the head forward (pushing) and backward (withdrawing) to test the capabilities of the system, to hold the contact, and to limit the force.

5.1 Test Results

Figure 5 shows the sensor values, the target speed and the real speed during an exemplary trial. The sequence of actions in this trial was: holding position until contact (at C), pushing back (at P1, P2) and slowly withdrawing (at W1, W2) twice and at the end pushing (at P3) and withdrawing fast (at W3). The highest measured force is 2.3 N. The real maximum value is presumably higher since 2.3 N is outside of the force sensor's range.

The trial starts out of range of the distance sensors. Therefore, the sensor signals are noisy and the target speed is disturbed. The robot's movement is only affected slightly by the noise, since the robot's joint damping acts as a low pass filter. The robot requires ~10 s to drive the initial distance of ~40 cm.

At contact (C), the measured force exceeds the target force range. This shows that the impact speed is slightly too high. However, a lower impact speed is not possible, since it is equal to the minimum speed of the robot (around 2-3 cm/s). The controller immediately adjusts the target speed to correct the applied force. In the following phase of contact holding the force is below the target range. The controller increases the target speed to correct the force, but the robot does not follow the target speed due to its lower speed limit.

When pushing against the cup (at P1), the desired contact force is highly exceeded. The robot immediately adjusts the pressure and can be pushed to a desired position. After pushing, the subject withdraws (W1). The force sensor reports contact losses although the robot follows the movement without losing contact. The measured force spikes from 0 to 0.2 N and back. This is caused by a jump in the sensor's resistance at around 0.2 N. Forces below ~0.2 N are measured as 0. The contact is held due to the automatic mode switch of the controller. The controller switches to driving mode and follows the user whenever the force sensor reports a contact loss. It follows with minimal speed, since it is in close proximity.

From P2 to P3, the pushing and withdrawing is repeated and gives similar results. At W3, the subject pulls back fast and ends contact. The robot can not follow the fast movement since it is not allowed to move fast when in close proximity.

In the following interview the subject reported no painful forces during the trials even when forces above 2 N were applied.

6 CONCLUSION

The multi-sensor system enables harmless contact with the mouth of the user with a simple controller structure. The applied forces exceed the desired range but still cause no pain or discomfort. Due

Figure 5: Sensor and target data in test trial (C=Initial Contact, P#=Push phase, W#=Withdraw Phase)

to safety limitations, the robot can presently only drive around 2 cm/s in close distance. Therefore, the contact holding only works for slow, minor movements of the user.

Remaining noise after the distance measurement smoothing is filtered by the robot's damping. This enables the use of low cost distance sensors. The Bluetooth induced signal delay does not cause any instabilities in the control response.

The next steps in this research will be to combine the presented system with the mouth detection of [4] and to implement the drinking control. The tilt angle can be controlled by the signals of the force sensors at the contact points. A suitable control and a start/stop condition for the task have to be implemented. To improve the overall control, the impedance control might be exchanged by direct force control. This enables the robot to react immediately to force changes without the control loop and bypasses the minimum speed limitation.

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