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Sensors for Assistive Robotic Drinking with Physical Contact

Steffen Schöllmann
Electrical Engineering and Applied Sciences
Westphalian University of Applied Sciences
Gelsenkirchen, Germany
steffen.schoellmann@studmail.w-hs.de

Pieter Try
Electrical Engineering and Applied Sciences
Westphalian University of Applied Sciences
Gelsenkirchen, Germany
pieter.try@w-hs.de

Lukas Wöhle
Electrical Engineering and Applied Sciences
Westphalian University of Applied Sciences
Gelsenkirchen, Germany
lukas.woehle@w-hs.de

Marion Gebhard
Electrical Engineering and Applied Sciences
Westphalian University of Applied Sciences
Gelsenkirchen, Germany
marion.gebhard@w-hs.de

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***Abstract*—This paper proposes two sensor systems for human robot interaction in assistive drinking tasks for motion impaired people. The first sensor system uses a capacitive and resistive sensor to detect proximity and measure contact forces between the user and a regular drinking cup. The cup is held by a robot with a three finger gripper. Control strategies for the drinking process with a regular cup using both the capacitive and resistive measurements were developed and tested. The control strategies were rated by the subjects with a NASA RTLX questionnaire. Statistically significant differences between both strategies are not evident. The second sensor system uses a System on Chip (SoC) with four sensors. It enables motion impaired users to stop the robot without contact to the robot. This is accomplished with a robust detection of a human blowing on the sensor. A sensor fusion algorithm is used for detection. The results suggest the usage of both sensing methods in further robotic systems. However, the detection of a human blow should undergo further tests with motion impaired people.**

Keywords— assistive robots, drinking task, sensor fusion, human-robot interaction, input modalities

I. Introduction

Every year 250,000 to 500,000 people worldwide sustain a spinal cord injury (SCI) [1]. Caused by accidents or diseases, SCI can lead to tetraplegia, the total loss of control and sensation on all four limbs and torso. Many people with severe motor impairments, such as people with tetraplegia, require caregivers for activities of daily living (ADLs). Robotic assistance systems offer the potential to provide a degree of independence to the affected person, but also have the potential to reduce the workload on caregivers.

Assistive robotics has been an active field of research in the past years. However, there is limited work towards robotic assistance with the ability to establish physical contact between the user and the robot, a skill needed for many ADLs. One example is independent drinking, which has been marked as a high priority in a survey with potential users [2]. Assistive robotic systems for drinking with physical contact need to perform several tasks. The cup has to be filled with a requested liquid (task 1). The robot has to grasp the cup (task 2) and drive to the user from an arbitrary starting position until the cup is in closest vicinity to the user (task 3). Contact between the cup and the user´s lips is established with defined, limited contact forces (task 4). Afterwards the robot performs a tilting motion to enable the user to drink while simultaneously maintaining the contact (task 5).

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Various systems have been developed to enable people with severe motor impairments to accomplish ADLs independently.

One of these systems is the FRIEND II assistive robot, it functions as a development platform towards more independence for people with tetraplegia and consists of an wheelchair mounted robotic arm and supplementary hardware for various tasks [3]. A later version of the system, the FRIEND IV, enabled a person with tetraplegia to carry out her work as a librarian but didn´t address the drinking task [4].

Huete et al. presented the ASIBOT assistive robotic system to handle a variety of different tasks such as eating and drinking. It can autonomously climb between different docking stations and perform the tasks from the most suitable position. The ASIBOT robotic system cannot enter a safety volume surrounding the user. It stops as soon as it enters the safety space and therefore can only perform the task of assistive drinking with a straw [5].

A different system to accomplish the drinking task was developed by Schröer et al. It uses a Kinect RGB-D camera and computer vision to localise the cup and the users mouth. The user gives Go/No-Go signals which trigger predefined motions for the drinking tasks. The hardware for the control input, a brain-machine interface realised through an EEG cap, needs to be attached to the user. This limits the independent use of the system, as the user cannot put on the cap without help [6].

Goldau et al. use a feeding cup with two resistive sensors and a Realsense RGB-D camera. The system does not require any physical interface to be worn by the user. The user controls the drinking motion by applying pressure on either of the resistive sensors on the drinking beak of the feeding cup. The author mentions that the users would have preferred a regular cup compared to a feeding cup [7].

This paper presents a system that covers task 3 up to 5, including Human-Robot Interaction. Task 1 and 2 are described in a paper which is to be submitted in 2021. The presented system consists of an ultra-lightweight robotic arm (Jaco 7-DoF, Kinova Inc., Canada) which grasps a regular cup. A capacitive and resistive sensor (Plyon medium, tacterion GmbH, Germany) is attached to the front of the cup. It is used to sense the contact between the user and the cup, both resistive and capacitive. The abort command is activated by blowing on a SoC (BME680, Robert Bosch GmbH, Germany) on the robot's wrist. The entire system set-up is established in the research project MobILe [8].

In contrast to the previous work, the proposed system consists of a conventional stereo RGB camera in combination with a low-cost time-of-flight (ToF) distance sensor for the approach. A sensor to monitor the contact forces of the drinking process and the proximity of the user with capacitive and resistive measurements is used. This enables the usage of a regular cup (not a feeding cup) without having to continuously apply force throughout the whole drinking process. A sensor SoC with four sensors and a microprocessor is used to detect a human blowing on the sensor as input modality. Giving the user an additional action to command the robot. The proposed system is designed for the drinking process without supplementary sensorized interfaces that have to be worn by the user.

The following sections 'Methods', 'Experiments' and 'Results and Discussion' are organised each in three subsections. The subsection A. covers the '*User detection and contact measurement*' with a capacitive and resistive sensor. The subsection B. covers two different '*Drinking strategies*' to control the drinking process with the resistive and capacitive sensor. The subsection C. covers '*Human blow as an input* modality' to allow people with tetraplegia to command the Robot to abort the drinking process.

II. Materials

The presented work uses the ultra-lightweight robotic arm Jaco 2 with a three finger gripper from Kinova (see Figure 1 A) [9]. The seven degree of freedom (DoF) arm is suitable for the use on an electric wheelchair. This robot system is developed particularly for assistive robotic tasks and is extensively tested in this context [10].

A commercially available Tacterion Plyon medium sensor (see Figure 1 B) with a resistive working range from 0,5 up to 15 N/cm^2 is attached to a regular plastic cup [11]. The capacitive properties of this sensor are investigated in this work. The cup is made of PVC/PU and has a diameter of 73 mm and a height of 103 mm [12]. The injection-moulded draft angle was removed from the upper part of the cup by a turning machine. This allows plane mounting of the sensor.

To detect a human blow, the Bosch BME 680 sensor SoC (see Figure 1 C) with pressure, temperature, humidity and concentration of Volatile Organic Compound (VOC) sensing and a microcontroller (Arduino Due 32-bit ARM core, Arduino, Italy) is used [13]. The low power sensor is operated in forced mode with the registers for oversampling set as 001. The register for the internal IIR filter is set as 000. The gas heating is configured as 400 °C for 70 ms. The settings result in a sample rate of approximately 12 Hz.

An infrared tracking system by Qualisys is used as external reference system. It consists of five Qualisys (Qualisys Miqus M3, Qualisys AB, Sweden) cameras [14] and passive IR marker trees attached to the Robot (see Figure 1 D) and the subject. A Unix computer combines all sensors and controls the robot with a system developed on top of the open source framework Robot Operating System (ROS) [15].

In all tests conducted with subjects, the maximum velocity of the robot´s end effector is limited in accordance with DIN ISO/TS 15066 [16]. The maximum permissible speed of the end effector has been determined in advance with empirical tests on a mock-up and is approximately 45 mm/s.

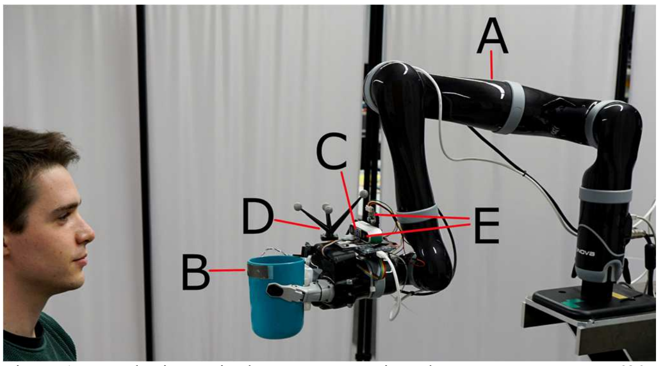

Figure 1: A - robotic manipulator, B – Tactetion Plyon sensor, C – BME680, D – marker tree for Qualisys system, E – camera and ToF sensor.

III. Methods

A. User detection and contact measurement

Information about the physical contact between the cup and mouth is provided by the Tacterion Plyon sensor. The capacitive properties can be used to detect the user or other objects within its proximity. The sensor´s capacitance changes throughout the last mm of the approach due to the presence of the users lips, which have a high dielectric constant in relation to air. A study with ten subjects was conducted to determine the average distance between the user and cup at the moment of capacitive detection. This information can be used to validate the measurement of the vision based localisation system which lacks precision in close proximity to the user due to occlusion of the user's mouth.

The capacitive read-out C strongly depends on the dielectric scenario. All materials, like objects, obstacles, cup, liquid level in the cup show impact on the capacitance. Therefore, the change of capacity $\partial C/\partial t$ over time is used to detect the user. The user is considered as detected if the gradient exceeds a certain threshold value C_T.

$$\frac{\partial C}{\partial t} > C_T \tag{1}$$

The capacitive read-out without objects in proximity of the sensor is recorded over a period of five minutes in order to determine the value of C_T. The value of C_T is determined to correspond to this reference measurement.

The resistive readout is depending on the pressure on the sensor. This pressure is the contact force divided by the area of contact between lips and sensor. This can be used to detect physical contact, but it requires contact forces high enough to exceed the minimal resistive detectable pressure value. Both, the resistive and the capacitive measurement are used to control the drinking process. The drinking process starts when contact between the lips and the cup is established.

B. Drinking strategies

The drinking motion is a rotation around the contact point with the user's lips (roughly the rim of the cup) and a translational upwards movement. Since the desired drinking speed varies depending on the user's condition and the liquid in the cup, the speed is controlled by the user. The presented work uses a sensor with two input parameters, the capacitance and the resistive measurement. Two different strategies to control the drinking process are developed and tested. Both strategies use the capacitive and resistive values as input.

Both strategies contain a so-called standby condition, in which the cup is in contact with the user and not moving. This position can be used by the user to take a break or swallow the liquid. The capacitive gradient is used to detect if the user and the cup are in contact. To exit the drinking mode, the user can retract the lips from the cup. The resistive reading is used in both strategies to detect whether the user is applying force to the cup or not. This information is used in different ways by the two strategies.

Figure 2 depicts the developed control strategies. Control Strategy 1 – "Press and Release" incorporates a discrete press and release event counter that can be compared to counting clicks of a computer mouse. A click is defined as an increase of the contact force above a pre-set threshold following a release by the lips of the user. After a click the user has one second to trigger another click which increments a counter. If the time expires and the user has not clicked again, the counter is evaluated. If the user clicks two times, the cup rotates to allow the user to take a drink. If clicked four times, the cup tips down a little (to avoid spilling any liquid) and moves away from the user. The click counter only allows exact click matches of two or four clicks to be interpreted as an action. For other numbers of the counter no action is triggered and the counter is reset.

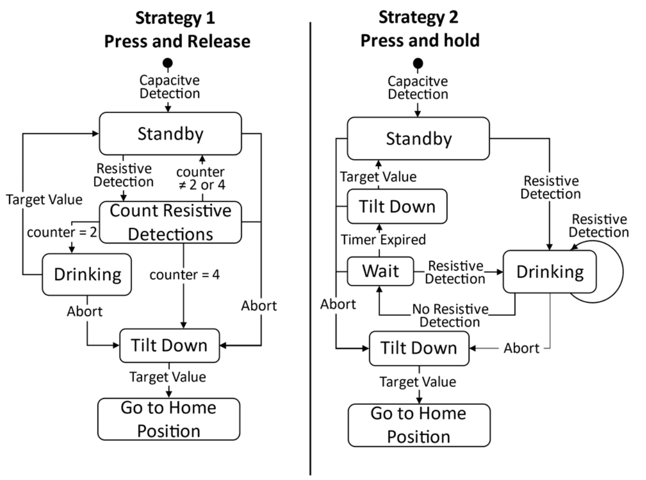

Figure 2: Schematic representation of strategy 1 and 2. Definition: Resistive Detection = user applying force, Capacitive Detection = capacitive detection of subject, Abort = force too high or user seperated, Target Value = target tilt angle.

Control strategy 2 – Press and Hold employs a press and hold mechanism. The robot continuously and slowly performs the drinking movement as long as the user applies force to the sensor. If the user releases the force, for example to swallow, the cup stops for 3 seconds. If the user applies pressure again within this time, the drinking process continues. If the time expires without the user applying pressure, the cup tilts down so that no liquid is spilled and the software returns to standby. To stop the drinking process, the user has to separate the lips from the cup, while in standby.

In both strategies, the drinking process is aborted if either too much force is applied or if the lips separate from the cup.

C. Human blow as an input modality

A crucial component of the safety concept is the ability of the user to stop the robot at any given time. A method proposed in Goldau et al. [7] uses computer vision to detect the head orientation as a condition to abort the robot. However, when the robot is in proximity of the user the recognition of the user's head can be disrupted due to the field of view of the camera and occlusions.

Therefore, the detection of a human blow via sensor fusion is investigated as an input modality to detect a user's intention to abort the process. In this case a blow is defined as a deliberate directional exhale.

The sensor SoC BME680 [13] is used to detect a human blow. It combines four sensors (air temperature, air pressure, air humidity, VOC) and a microcontoller, see Figure 1 C. The sensor is mounted behind the cup and above the cup rim. In this position the user can blow on the sensor during all stages of the assistive drinking process. The algorithm to detect the blow is shown in Figure 3. The sensor data is processed individually for each quantity. The individual sensor data is filltered using individual digital bandpass filter to reduce ambient noise. Subsequently the signals are squared to ensure that all signals are positive and to give greater weight to larger amplitudes. In addition some signals are scaled to enabel visualisation of all signals in one plot. A human blow is detected and the robot is stopped if at least two sensor values exceed their thresholds within a pre-defined period of time.

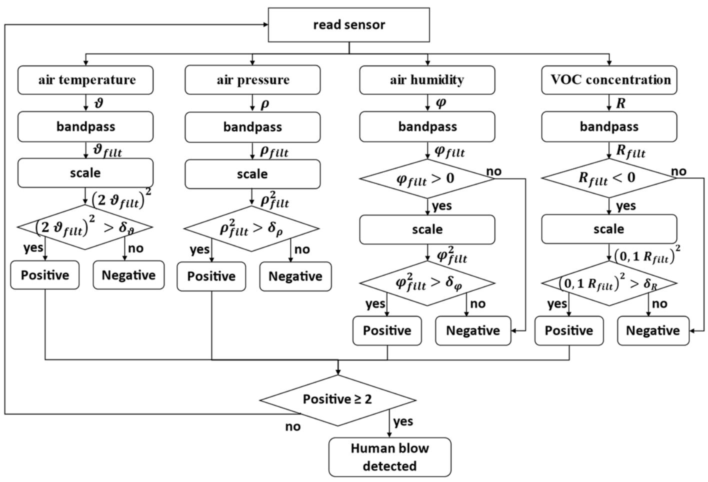

Figure 3: Sensor fusion algorithm to detect a human blow.

IV. EXPERIMENTS

The study has been conducted in three parts and with ten able-bodied subjects. Due to the covid-19 pandemic it has not been feasible to test the proposed system with people affected by tetraplegia. The age of the subjects ranged from 22 to 57 years (mean ± standard deviation (SD): 32,5 ± 13,3 years). Eight of them are male and two are female. All subjects gave their written consent to the experiment and were instructed in detail about the procedure. This study has been approved by the ethics committee of the German Association of Social Work (DGSA).

A. User detection and contact measurement

A study has been conducted to evaluate the detection of physical contact with the user based on the capacitive and resistive measurement. The subject has been positioned in front of the robot which has the cup with the sensor grabbed. The gripper has been positioned in front of the subject. In the test the robot has approached the subject in a straight path. The position of the robot and user are tracked with an IR camera system. The robot stops when contact is established and returns to the start position. The supervising research assistant uses a button to mark the first contact between lips and cup. The approach is repeated 50 times with each subject.

During the tests an (IR) tracking system by Qualisys was used to determine the distance between the cup and the user. The accuracy of the used Qualisys system depends on the calibration and distance between camera and marker tree. The accuracy in the given setup is at all time better than 1 mm. It uses IR marker trees (D in Figure 1) to estimate the pose of objects. A marker tree was mounted on the robot's wrist. The cup was grasped by the gripper of the robot. It stayed in a fixed position in relation to the tool centre point (TCP) of the robot and therefore fixed in relation to the marker tree throughout the whole experiment. The subject had to use the lips to make contact, thus the marker tree cannot be attached to the lips. Therefore, the user was tracked with an IR marker tree on the forehead. The relation between where the lips come into contact with the cup and the marker tree varies due to different skull shapes and the ductile nature of the lips. To determine the absolute distance between the lips and the cup, the timestamp when the lips came into contact with the cup were marked manually for every experiment. The distance between the lips and the cup were calculated with the pose measurement of the external IR reference system and the manually determined timestamp.

The manual determination of the timestamp results in a systematic error. The human reaction time is added to the time of contact given that the research assistant had to press a button to mark the time of contact. This systematic error is compensated by subtraction of the reaction time from the marked timestamp. A reaction time of 218 ms (age group 18-24, reaction to visual stimulus) has been used for the error compensation [17].

B. Drinking strategies

Two strategies to control the drinking process were proposed. Both strategies were tested in a study to evaluate their performance. The strategies were explained to the subjects, followed by one minute of free testing for each strategy. After the testing phase, the subjects were assigned to simulate the drinking process three times per strategy. The drinking simulation was completed when the subject tilted the cup to approximately 45 degrees and stopped the drinking procedure.

Due to Covid-19 the hygiene policy has required to cover all surfaces which cannot be disinfected with a thin replaceable plastic sheet. The used sensor is not approved for contact with disinfectant and thus had to be covered. The process has been conducted without liquid in the cup because the plastic sheet would have led to spillage.

After performing the assigned tasks, the subjects were asked to evaluate the strategies by completing a NASA raw task load index (RTLX) questionnaire for each strategy.

C. Human blow as an input modality

The usage of a human blow as an input modality for event based stopping of the robot is proposed. A study was conducted as a proof of concept and to investigate if the performance changes with increased distance. The detection of a human blowing on the sensor was tested at three different distances between the sensor and the user's lips. Those are 17 cm, 32 cm and 47 cm. At 17 cm the subject's lips are in contact with the cup due to the mounting position of the sensor. The distance 47 cm is chosen as prior test suggested this as maximum measurement range, 32 cm are chosen for equidistant distances between the three positions. The position of the sensor is shown in Figure 1. Spacers were installed so that the subjects can reproduce the positions for 32 cm and 47 cm. During the tests, the test subjects were seated in front of the robot as they would during a drinking process. Each subject was asked to blow twelve times on the sensor. Four times from each of the three distances in a randomised sequence. The subjects had a one-minute break between every blow. The subjects were instructed to blow firmly on the sensor for about one second. Also, it has been emphasised that it is important to aim precisely at the sensor.

V. RESULTS AND DISCUSSION

A. User detection and contact measurement

A study was conducted to investigate the capacitive properties of the sensor. In total 500 approaches are recorded and the distances of the first detection of the lips are evaluated. The systematic error imposed by the human reaction time (see chapter Experiments) is compensated in the presented results. On average, the subjects are detected at a distance of 8.2 mm ± 2.0 mm between the sensor and the lips. Figure 4 shows a histogram with the results of all approaches. The x-axis represents the distance, and is divided into segments of 0.25 mm. The y-axis represents the number of measured distances for each segment.

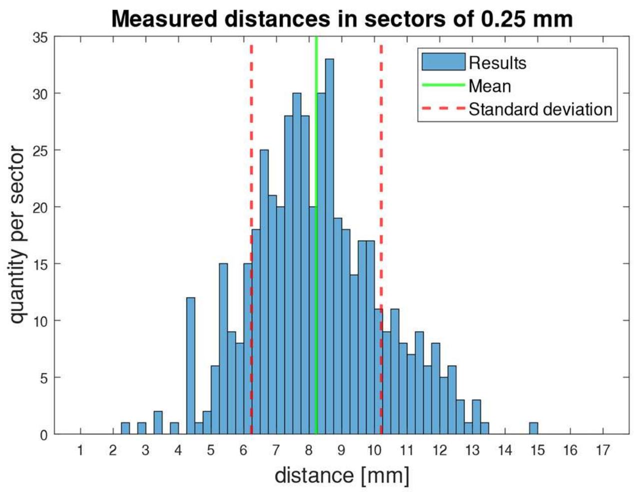

Figure 4: Distribution of measured distances

By subject, the mean value of all ten subjects is between 7.03 mm and 8.53 mm. The standard deviation lies between 1.09 mm and 2.08 mm.

The results show that the subject can be recognised with the capacitive sensor before the establishment of contact between lips and cup. The average distances do not show any large deviation between the subjects. This additional data can be used in combination with a vision-based system to improve the user detection in proximity. In contrast to systems that rely exclusively on image processing, this process enables the robot to establish physical contact. Vision based localisation systems lack precision in proximity to the user due to occlusion of the user's mouth.

B. Drinking strategies

By using a resistive sensor with capacitive capabilities, two input parameters to control the robotic system and the drinking motion are available. Two different control strategies are investigated. Figure 5 shows the results of the NASA RTLX questionnaire. The results for strategy 1 – Press and Release are shown in blue and the results for strategy 2 – Press and Hold in red. The standard error mean is shown as a vertical line. The questionnaire consists of six questions: (1) how mentally demanding was the task? (2) how physically demanding was the task? (3) how hurried or rushed was the pace of the task? (4) how successful were you in accomplishing what you were asked to do? (5) how hard did you have to work to accomplish your level of performance? (6) how insecure, discouraged, irritated, stressed, and annoyed were you? Figure 5 depicts the average results for all ten test subjects.

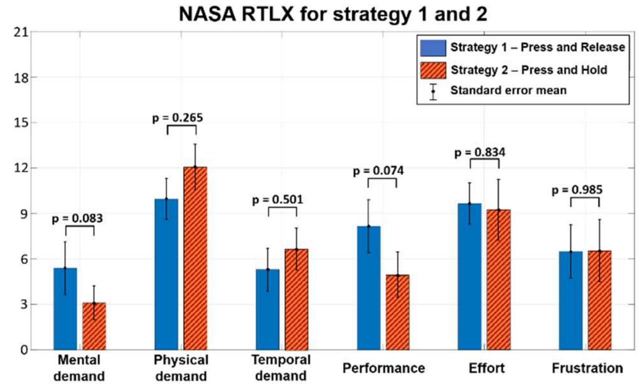

Figure 5: NASA RTLX results for strategy 1 and 2

The subjects have chosen between 0 and 21 points for each category. In category (4) performance the 0 represents perfect and the 21 represents failure. In all other categories the value 0 represents very low and the value 21 represents very high. The p-value, which is determined by the paired sample t-test, is displayed above each category.

The cumulative score for both strategies is below 50, which indicates a low task load. The score for strategy 1 is 44.95 and 42.55 for strategy 2. According to the significance level $p < 0.05$, a statistical significance is not evident in any of the categories.

However, one noticeable difference is the larger mental load for the strategy 1. This is plausible because strategy 1 requires the subjects to perform clicks and count how many clicks were performed. With strategy 2, the subjects only had to maintain the pressure. In addition, many subjects rated their performance in strategy 2 with ~4.5 better than in strategy 1 with ~8. The categories physical demand and effort have the highest values. This indicates that the necessary pressure to activate the resistive sensor and therefore tilt the cup, is high. This is also reflected by the verbal qualitative feedback from several subjects. They stated that the force required to activate the resistive sensor is rather high.

C. Human blow as an input modality

The combination of four sensors as event driven control to stop the robot was investigated as a proof of concept. The tests were evaluated by determining the number of detections at the distances of 17, 32 and 47 cm.

At a distance of 17 cm and 32 cm, the blow is detected in 39 of 40 times each after sensor fusion. At 47 cm, 36 of the 40 blows are detected after fusion. Figure 6 shows the results broken down by distance and sensors. The first four bars show the number of detections with the respective sensor. The four sensors are labelled as follow. Air temperature ϑ, air pressure ρ, air humidity φ and the concentration of VOC gases R. The fifth bar $\sum$ shows how often the blow is detected by the combination of the four sensors with the algorithm as described in Figure 3. Each subject blew four times per distance. Thus, 40 blows were recorded for every distance.

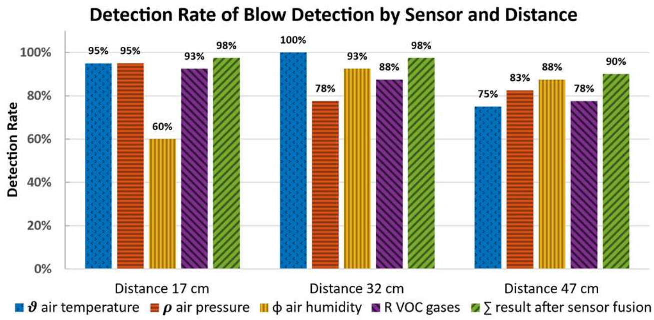

Figure 6: Results for the detection of a human blow on the sensor by sensor and distance

At 17 cm the humidity sensor detected the least blows. At 32 cm the air pressure sensor detected the least blows. However, at 47 cm the humidity sensor and air pressure sensor detected more blows than the temperature and VOC sensor.

In 114 out of 120 cases the blow could be detected through the combination of the four embedded sensors. The proposed algorithm that requires at least two sensors to trigger to evaluate an event as a human blow appears to be suitable for the tested subjects. The number of sensors that have to be triggered to detect an event as a human blow can be increased to improve the false-positive-rate. However, this is a trade-of that also results in a higher false-negative-rate.

Observations during the tests show that subjects with a stronger blow are detected more easily. Subjects 3 and 10, for example, stated that they do a lot of sport and have a detection rate of 100 %. Subjects with a weak blow had a lower detection rate, subject 8 58%, subject 1 71% and subject 4 77%. Therefore, a higher error rate can be expected in the target group of people suffering from tetraplegia. In each of the tests, only one blow was made. During a real drinking process, it is possible to blow several times if the robot does not react, especially at longer distances. At short distances, where the robot has to react quickly to avoid hazardous situations, the performance of the system is better (see Figure 6). The results indicate that the sensor and the detection algorithm are suitable to be used as an intentional abort mechanism in a robotic system.

VI. Conclusion and Future Work

This work proposes the use of two sensor systems for robotic assistive drinking. A sensor for resistive force measuring is attached to a regular cup and is used to detect the contact forces between cup and the user's lips. The capacitive properties of this sensor are investigated to detect the proximity to the user before contact is made. Experiments show that subjects are first detected at a distance of 8.2 mm ± 2.0 mm between cup and lips. This method of user detection enables a safe establishment of contact between cup and user, as vison-based systems often lack the precision due to occlusion of the user's mouth. In future studies the systematic error compensation could be avoided by determination of the timestamp of contact establishment with an additional video stream containing a close up of the Subject´s head.

Two strategies for the human robot interaction during the drinking process are proposed, a discrete "Press and Release" event counter and a continuous "Press and Hold" mechanism. A user study shows no statistically significant preference for either control strategy, but it is evident that the needed contact force to perform the drinking process is too high in both strategies. In future work it will be necessary to further decrease the required contact force by the development of a control strategy that relies more heavily on the capacitive sensing.

The robust detection of a human blow on a commercial sensor SoC via sensor fusion provides the user with an additional input modality. The proposed combination of air pressure, air temperature, air humidity and VOC concentration is tested with ten able-bodied subjects as proof of concept. The results suggest the usage of this interaction modality in future assistive robotic systems. However, a study with strongly motion impaired people will be conducted in future work, as this was not possible due to Covid-19 restrictions. Furthermore, the integration of a second sensor on the front of the cup will be investigated within this study.

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