Towards safety in Physically Assistive Robots: eating assistance*

Maria Vila, Gerard Canal, Guillem Alenyà[1]

Abstract— **Safety is one of the base elements to build trust in robots. This paper studies remedies to unavoidable collisions using robotics assistive feeding as an example task. Firstly, we propose an attention mechanism so the user can control the robot using gestures and thus prevent collisions. Secondly, when unwanted contacts are unavoidable we compare two safety strategies: active safety, using a force sensor to monitor maximum allowed forces; and passive safety using compliant controllers. Experimental evaluation shows that the gesture mechanism is effective to control the robot. Also, the impact forces obtained with both methods are similar and thus can be used independently. Additionally, users experimenting on-purpose impacts declared the the impact was not harmful.**

I. INTRODUCTION

The need for assistive care is rapidly increasing, and it will further increase in the following years. For instance, the EU expects a 34% increase in the total number of stroke events [1], with also an increase in the number of stroke survivors who may potentially need assistive devices. Part of this effect will be motivated by the increase of aging population, which will require even more gerontology assistants such as nurses, numbers with which we may not be able to cope [2]. Therefore, the need for assistive technologies such as robots will be a key factor in the well-being of the elderly and handicapped population.

However, this kind of robots pose big research and ethical challenges on the table. Physical assistance, such as feeding [3] or dressing [4] require close contact in highly sensitive areas of the body. Accordingly, safety should be a main focus of research in the Physical Assistive Robots community. In this paper, we will focus on the safety aspects of a physical assistive task such as helping a user to eat autonomously. We propose safety measures in two ways. The first one is preventive, monitoring the user and ensuring to perform the actions in safe moments. The second one is focused in recovering from unavoidable issues such as impacts, stopping the robot before it can harm anybody and recovering from that in order to finish the task.

II. RELATED WORK

Physical Assistive Robots (PAR), in contrast with Socially Assistive Robots (SAR), need to be inherently safe for the user being assisted. Many works have shown the concern regarding safety in PAR. An example is the work by Alami *et al.* [5] which analyses safety issues as well as many injury criteria, some of which will be applied in this paper. Other works show different concerns and motivations on safe PARs [6], [7], [8]. Nonetheless, safety is also important in SAR systems which, even they do not include physical contact in the task, are moving in the same environment and can cause accidental harm to the user [9]. Rehabilitation robotics are focused in helping the user to recover from some health condition, be it physically or socially. Thus, this kind of robots should also be inherently safe [10].

A specific case of physical assistance is the feeding aid [11]. Feeding involves not only contact but the insertion of cutlery in the user's mouth, which increases the chances of harming the person. Available feeding assistance systems are usually of three kinds. In manually operated eating systems, such as the neater eater[1], the user approaches the device to the mouth in order to eat, helping users with mobility issues. Forearm stabilizers provide an arm support, successfully stabilizing the arm of the user. Some examples can be found in [12]. Finally, electrically operated eating systems are robotic arms with an attached cutlery piece that can move autonomously, such as the one we are using in this paper. There are many examples available, such as [13], [14], [15], although most of this kind of systems lack of enough sensory information to provide a full feeding assistance, as well as to ensure the safety of the user when doing it. However, some authors such as Park *et al.* [16] have started to analyze possible hazards towards the user by detecting anomalous executions.

In this paper we differentiate between strategies to avoid collisions and strategies to treat unavoidable collisions. For the latter, we study two different strategies (passive and active) to minimise potential harm.

III. SAFETY STRATEGIES FOR AUTONOMOUS FEEDING

Eating assistance is an invasive task, thus the user needs to feel safe and in control of the robot behavior. We propose to use gestures and an attention mechanism to wait for the user's attention and readiness to eat providing feeling of control and safety.

The feeding system works as follows. Once the spoon is loaded with food, the robot waits for the user's attention to approach the mouth. Then, the robot moves to the *pre-feeding position* (manually set at 30 cm in front of the mouth). The robot waits for the user to open his mouth while he is looking

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[1]Authors are with Institut de Robòtica i Informàtica Industrial, CSIC-UPC, C/ Llorens i Artigas 4-6, 08028 Barcelona, Spain. {mvila,gcanal,galenya}@iri.upc.edu

[1]www.neater.co.uk/neater-eater

directly to the spoon. When this occurs, the robot feeds the user, goes back and starts the process again. The loading of the spoon is done using a pre-programmed motion as it has no influence on the safety problem.

Next we present how the user can take control of the robot to set the eating cadence and avoid contacts, and the safety strategies that can be used to minimize the effects in case of undesired collisions.

A. Attention and gestures

An effective strategy to avoid collisions and provide the user with the control of the task is to use gestures and an attention mechanism. The user is considered to be paying attention to the robot if his head orientation allows him to look at the spoon. Head orientation, which is represented with Euler angles, is obtained using OpenFace [17]. If the angles obtained are inside the ones presented in Table I the user is considered to be paying attention to the robot.

	Minimum value [rad]	Maximum value [rad]
ϕ	-1.35	0
θ	-0.5	0.5
ψ	-0.6	0.6

TABLE I

EULER ANGLES FOR THE ATTENTION DIRECTION. VALUES DEPEND ON THE PARTICULAR FEEDING POSE WHILE RANGE BETWEEN MIN AND MAX IS GENERAL.

Once the user's attention is towards the spoon, it is essential to detect whether the mouth is open or not. The spoon will only enter the user's mouth if it is open, thus the user has total control of the start of this movement. The state of the mouth is obtained through the user facial landmarks, gathered with OpenPose [18]. Concretely, it has been computed with a comparison between the lip size and the space between the lips. The mouth is open if the following expression is evaluated as true:

$$((LSI - LSS) + (LII - LIS)) \times 1.4 < (LIS - LSI),$$

where 1.4 has been determined empirically, LSI is the average height of the landmarks of the inferior part of the superior lip, LSS is the average height of the landmarks of the superior part of the superior lip, LII is the average height of the landmarks of the inferior part of the inferior lip and LIS is the average height of the landmarks of the superior part of the inferior lip.

If the mouth closes or the head turns when the spoon is approximating the mouth, the robot will go back to the *pre-feeding position*. From this position it will only try to enter the mouth again if the the mouth is open and the user's attention is towards the spoon.

An RGB-D camera, attached to the robot gripper (Fig. 1), is used to identify and cope with not accurate enough head and mouth detections. Detections are not accurate enough if the distance between the user's face and the camera is smaller than 40 cm.

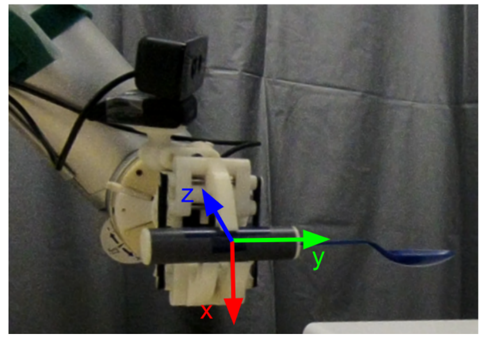

Fig. 1. Robot gripper with its axis and RGB-D camera

B. Safety stretegies

Safety is essential as in feeding exists direct contact between the user and the robot. Even if the user is in control of the robot behaviour as explained in last section, undesired collisions may occur. For this case two different types of safety have been considered: passive and active safety.

Passive safety is achieved implementing a compliant robot controller [19]. By using a friction model, the control signal based on the position error is minimal and in case of impact low forces will be applied. However, after the impact the position error is still present so the robot will continuously try to apply some force to try to reach the desired destination. Note that using this controller exists a trade-off between compliance and movement precision.

Active safety is achieved by limiting the maximum force. A force sensor (mounted between the robot end-effector and the gripper) is used to obtain force and torque values at the end-effector.

For the experiments we have manually set the force thresholds (in our setup in the y direction) for the two potentially harmful situations (see Table II): the entering into the mouth where low forces are expected, and the exit where force is inherently part of the task.

	Minimum value [N]	Maximum value [N]
Enter mouth	-1.5	4
Exit mouth	-7.1	4.5

TABLE II

FORCE LIMITS FOR THE ENTER AND EXIT MOUTH TRAJECTORIES

When a force limit is exceeded the robot remains one second in the *waiting position* that consists on gravity compensation. When finished, if the spoon is full, the robot will move to the *pre-feeding position* and wait for the mouth opening. Alternatively, the robot will go back and re-start the feeding process again.

IV. EXPERIMENTAL EVALUATION

In order to test the proposed robot behavior and its safety, two experiments have been performed. The first one has been developed to analyze the safety of the system and thus they have been carried out without real users. When the safety of the system has been confirmed, more experiments have been performed, this time with real users.

A. Active safety vs. passive safety

To perform this experiment a picture of a person opening the mouth has been fixed on a wood panel. This wood panel is strong enough to support the robot's force without moving or bending.

This experiment consists on the robot moving towards the picture with the same movement that it performs when entering the user's mouth. However, in this experiment the robot will impact with the wood panel.

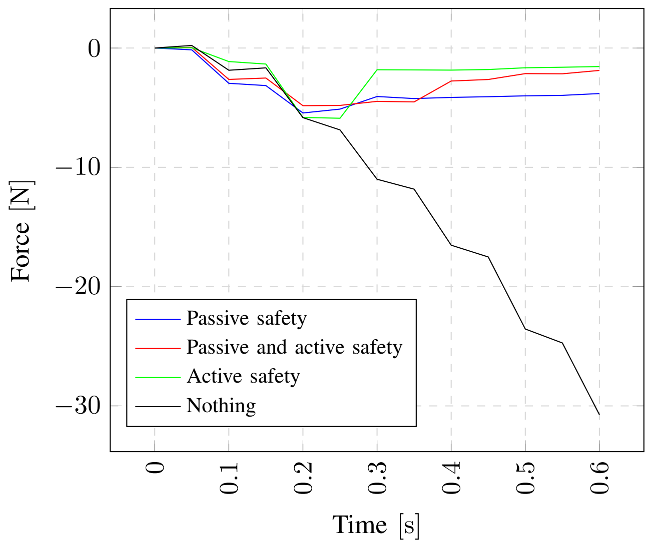

Fig. 2. Comparison of the y-axis force for the four setups

This experiment was performed with the four setups resulting of the combinations of passive and active safety. The impact forces in the y-axis obtained for the four setups are shown in Fig. 2. As it can be observed, the setups without passive safety have a higher impact force, reaching the $-5.8N$. Around the second 0.3 the active safety setup decreases the force reaching the *waiting position*. On the other hand, the passive safety setup decreases the force remaining at $-4N$ as it is trying to reach the desired position. The combined active and passive safety setup also remains at $-4N$, although at the second 0.4 it reaches the *waiting position* arriving at $-1.6N$.

With this results it is clear that both safety strategies offer a safe task performance as the peak forces never reach harmful levels. Therefore, setups with at least active or passive safety can be used.

However, in most of the experiments conducted with passive safety there was food spilling and thus, the task could not be finished properly.

Passive safety offers a safer operation as the robot reaches lower forces. However, the difference of peak forces between passive and active safety is only of $1N$, so it is not a determining factor. On the other hand, passive safety does not decrease the applied force over time which can discomfort the user. Moreover, setups with passive safety have less precision which causes food spilling. Therefore, the setup chosen for the second experiment is the one that only offers active safety as it assures a safe impact and a precise and comfortable task performance.

B. Experiment with users

The prototype was tested in 104 executions with 10 able-bodied participants. Each user was asked to perform some specific tests with anomalies and some free-form tests. An example of a successful execution can be observed in Fig.3.

Fig. 3. Successful execution of the feeding task

With the user tests, many elements of the system were evaluated. First of all, we evaluate the preventive safety. To do so, users were asked to look at a side and turn the head to compute the average reaction time of the robot to a change in the visual state of the user. In the head orientation experiment, we had an average reaction time of 0.46 seconds with a variance of 0.14 seconds and all the user's movement detected correctly.

Then, the mouth openness detection was assessed in a similar way. In this case, the average response time was 0.44 seconds with a variance of 0.12 seconds, although in this case some users were not correctly detected by the face landmarking library, which highlights the importance of having the low-level safety exposed above.

Finally, users agreed to perform tests to assess the forces involved in contacts occurred while feeding. In this case, we performed an impact experiment and also a spoon retention one. In the first one, the robot was impacting with the user's face when entering the mouth. In the second, the user retained the spoon with their teeth, not letting the robot perform the exiting motion.

An example trace of the forces involved in this experiment is in Fig. 4. The first element is the impact, shown around the second 2 of the execution. In this case, the force reaches the $-4.5N$. Then, the robot remains in *pre-feeding position*

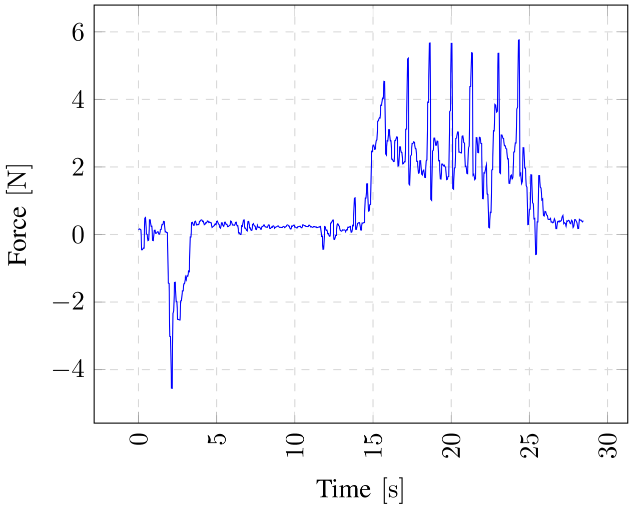

Fig. 4. Force in the y-axis of the impact between the user face and the spoon ($t = 2s$) and the user retaining the spoon ($t \in 15..25s$)

and performs the motion again, this time entering the mouth (second 15). Around second 17, the robot tries to leave the mouth but feels the user retention so it enters the *waiting position* to avoid any harm, and retries until a successful exit motion can be performed (second 25). The higher peak in this case is of $5.7N$ when trying to leave the mouth.

After the experiments, the users were surveyed and all of them agreed in stating that the impacting and retaining forces were not harmful, and that they felt comfortable during the experiment. Therefore, we guarantee that any unavoidable impact, although not pleasant, will not be harmful for the user. Moreover, it is also safe for the user to retain the spoon or even move it while it is inside the mouth.

V. CONCLUSIONS

A prototype of a robot capable of feeding a person autonomously in a safe manner has been proposed and tested. The robot movement is controlled by user's attention and readiness to eat, giving a sense of control and safety, and preventing dangerous situations that could be foreseen. This has been achieved by using visual information.

Two low-level safety measures have been tested: passive and active safety. The first one is achieved by using a compliant controller able to cope with disturbance in the movements. The other one actively monitors the force levels in the end-effector to prevent the application of excessive force against the user. It has been concluded that if the robot trajectories and force limits are correctly specified, both passive and active safety offer enough safety in the case of an unavoidable impact between the user and the robot. Therefore, passive and active safety are redundant. However, they can both be implemented to offer a major warranty of the robot safety.

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