Mathematical Description of Functional Motion and Application as a Feeding Mode for General Purpose Assistive Robots

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***Abstract*—Eating a meal is among the Activities of Daily Living, but it takes a lot of time and effort for people with physical or functional limitations. Dedicated technologies are cumbersome and not portable, while general-purpose assistive robots such as wheelchair-based manipulators are too hard to control for elaborate continuous motion like eating. Eating with such devices has not previously been automated, since there existed no description of a feeding motion for uncontrolled environments. In this paper, we introduce a feeding mode for assistive manipulators, including a mathematical description of trajectories for motions that are difficult to perform manually such as gathering and scooping food at a defined/desired pace. We implement these trajectories in a sequence of movements for a semi-automated feeding mode allowing the user to have control over the feeding pace. Finally, we demonstrate the feeding mode with a JACO robotic arm and compare the eating speed, measured in bites per minute of three eating methods: a healthy person eating unaided, a person with upper limb limitations or disability using JACO with manual control, and a person with limitations using JACO with the feeding mode. We found that the feeding mode allows eating about 5 bites per minute, which should be sufficient to eat a meal under 30min.**

***Index Terms*—component, formatting, style, styling, insert**

I. Introduction

EATING a meal is among the Activities of Daily Living (ADL) [1], but it is a difficult task for people with mobility and functional limitations, such as cerebral palsy or various levels of paralysis. For a meal to be enjoyable, it must be eaten at a reasonable pace with minimal effort [2]. Dedicated technologies, such as exoskeletons [3] and feeding robots, have been developed to assist these patients in eating independently [4]–[6], thus reducing the burden on caregivers.

Although many automated feeding devices are performing well [6]–[9], their operation relies on an almost perfectly controlled environment. This usually means that food is placed in a special plate, often attached to the robot to fix its location, and is picked up using a dedicated utensil. This makes it easier to hard-code trajectories that will pick up food every time, but makes self-feeding impossible as soon as any part of the environment is modified. These solutions are over-specialized (task-specific and tools-specific), often cumbersome and limiting, notably in terms of portability. These factors usually prohibit their use outside of the users home.

General-purpose assistive robots, such as wheelchair-based manipulators, are another option [10], [11]. They can be used for performing a variety of tasks [12], but these robots are hard to control for elaborate continuous motions such as eating [13]. Sustained effort and focus are required to eat a meal by manually controlling such a device; little to no automation is available for any given task. However, these robots are not limited to heavily controlled environments, making them significantly more versatile. Despite this potential, to our knowledge, no formal description of a scooping motion (nor other functional motions) was ever developed for free, uncontrolled environments.

The aim of this paper is to develop a semi-automated feeding mode for general purpose assistive manipulators which allows a user to eat a meal at a reasonable pace and with limited effort. This mode should offer enough flexibility to function for multiple plate locations and sizes. In the following sections, we will first present a mathematical framework for designing trajectories that will allow for this flexibility, as well as parameters mathematically defining scooping and food gathering motions to use as trajectories for manipulators. Then we will propose a sequence of motions for semi-automated feeding and integrate it with a simple 3-button interface. Finally, we will demonstrate our mode using a JACO robot (Kinova Robotics, Canada) to compare the pace of eating (in bites per minutes) while using the feeding mode to that of a healthy person and of a disabled person manually controlling the robot.

II. Configuration independent motion

In this section, we present a framework to create trajectories expressed in the tool frame, which are consequently independent of the robot configuration as long as the motion does not cross problem-inducing points like kinematic singularities or self-collisions. We then use this framework to design trajectories for scooping and food-gathering motions.

A. Tool-based trajectories

Since robots are usually designed to receive inputs (either positions or velocities) in the base frame, the most simple way to send tool-based trajectories is to express them in terms of velocities in the tool frame of reference and then to project said velocity in the base frame. Many robots would also accept inputs in the joint space (positions, velocities, torques). All joints must be controlled, so it is clear that any trajectory designed in the joint space would be configuration-dependent, which we want to avoid.

1) End-point control: The position of the tool frame relative to the inertial frame can be expressed in homogeneous coordinates through a transformation matrix given by eq. 1.

$$\boldsymbol{T}_{4\text{x}4} = \begin{bmatrix} \boldsymbol{R}_{3\text{x}3} & \boldsymbol{p}_{3\text{x}1} \\ \boldsymbol{0}_{1\text{x}3} & 1 \end{bmatrix}, \tag{1}$$

where:

- $\boldsymbol{R}$ is the rotation matrix representing the orientation of the tool relative to the inertial frame.
- $\boldsymbol{p}$ is the position of the tool relative to the inertial frame.

Then, a velocity along an arbitrary axis $\boldsymbol{v_u}$ expressed in the tool reference frame is given in the inertial frame by equation 2.

$$^{\boldsymbol{b}}\boldsymbol{v_u} = \boldsymbol{R}\boldsymbol{v_u} \tag{2}$$

All that remains is to express $\boldsymbol{v_u}$ as a function of time to describe a desired trajectory. However, it can be hard to visualize trajectories in terms of velocities, so we propose to design trajectories with positions and then take the time derivative to obtain the desired velocities.

2) Planar trajectories: Functional trajectories such as scooping can usually be described as a constant forward velocity in the tool frame with a varying orientation, which simplifies the trajectory description to a function of orientation over time and a fixed value of $\boldsymbol{v_u}$ in equation 2.

For a trajectory described by a polynomial, for example in the ZX plane of the tool frame, such as in equation 3

$$x(z) = \Sigma_{i=0}^{n} a_i z^i, \tag{3}$$

the orientation about the normal axis (here Y) is given by equation 4:

$$\theta = \arctan(\frac{dx}{dz}) = \arctan(\Sigma_{i=1}^{n} a_i i z^{i-1}) \tag{4}$$

By taking the time derivative, we obtain the angular velocity.

$$\omega = \frac{\Sigma_{i=2}^{n} a_i i(i-1) z^{i-2}}{1 + (\Sigma_{i=1}^{n} a_i i z^{i-1})^2 \dot{z}} \tag{5}$$

To generalize this method to a 3D trajectory, simply describe two perpendicular planar trajectories (say in the ZX and ZY planes) and add the angular velocities, which are orthogonal to each other.

Finally, the forward velocity for performing the motion in a given time t can be set taking the curve length as in equation 6:

$$v = \frac{1}{t} \int_0^{z_{max}} \sqrt{1 + (\frac{dx}{dz} + \frac{dy}{dz})^2} dz \tag{6}$$

B. Scooping motion

The scooping motion can be defined using the method described above. Assuming the scooping motion is in the ZY plane with the positive Z-axis oriented ”forward”, we are looking for a polynomial $y(z)$ with the following characteristics:

- $y(0) = 0$
- $y(2cm) = -0.5cm$
- $y(2cm)$ is a minima
- $\frac{dy}{dz}|_0 < 0$

This set of conditions was chosen empirically to describe a motion going down $0.5cm$ while going forward $2cm$ and rotating until the utensil is horizontal, based on our observations of a normal-looking scooping motion. These characteristics are respected by equation 7.

$$y(z) = -0.025z^3 + 0.225z^2 - 0.6z \tag{7}$$

Although it would seem appropriate to make use of a remote center of rotation to make certain that the trajectory is followed by the tip of the utensil, this would add constraints to the system, such as forcing a certain length of tool or requiring it to be measured. Because the tool is short, not using the remote center of rotation does not distort the motion to a significant degree. Therefore, to take advantage of the added flexibility of the system, we recommend not using a remote center of rotation.

C. Food-regrouping motion

After eating for a while, the remaining food will be scattered more or less randomly around the plate, further and further reducing the odds that scooping at a given location in the plate will grab a satisfying amount of food. The purpose of the food-regrouping motion is to gather the remaining food and bring it back to the center of the plate, where it can be more easily scooped. To achieve this, the main required motion is to follow the inner edge of the plate with a utensil perpendicular to the plate edge and describing a circular motion.

Although such a motion could be expressed in terms of polynomial derivatives, a perfectly circular motion can be obtained with simpler steps.

Given a motion speed $v[cm/s]$, following the edge of half a plate of radius $R[cm]$ will take:

$$t = \frac{\pi R}{v}[s] \tag{8}$$

During this time, the tool orientation must rotate of π, yielding a necessary angular velocity of:

$$\omega = \frac{\pi}{t}[rad/s] \tag{9}$$

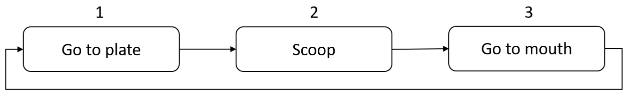

Fig. 1. Eating cycle

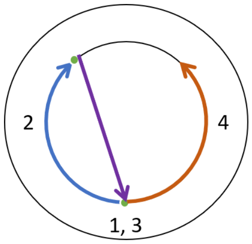

Fig. 2. Steps of the food regrouping sequence

III. Feeding mode for a general purpose assistive robot

The general idea for the feeding mode is to mimic the eating behaviour of a healthy person by scooping at various places in the plate and regrouping the food when it becomes sparse until the plate is mostly empty. In this section, we present the strategy behind the mode as well as some results from an implementation on the Jaco robotic arm (Kinova, Canada).

A. Strategy

As seen in the previous section, some knowledge of the scene must be known in order to perform the eating and food-gathering motion trajectories correctly. First, the radius of the plate must be known , although the accuracy of the measurement can be very rough, so an average value around 10-15 cm can be hard-coded according to the user's preferences. The position of the plate as well as the position of the user's mouth must also be known in order for the robot to complete the eating cycle properly. These positions may be indicated and recorded by manually driving the robot's end-effector to each of them before the beginning of the meal.

The process of eating a meal can be modeled as a loop consisting of sending the robot to the plate, scooping food and going back to the user's mouth, as seen in Figure 1.

Note that in order to scoop food efficiently, it is necessary to offset the initial position of the scooping motion because the motion from the previous loop will have moved the food.

Once a few eating cycles are performed, food is usually scattered. The food gathering motion can be called in such a sequence that most food should be moved back to the middle of the plate. Such a sequence is illustrated in Figure 2.

Because the motion is performed in logical sequence, the user interface is easily adaptable to the motor limitations of the users. Some form of button may be used for each part of the eating cycle (going to plate, scooping, going to the user), but we found most convenient to simply use two buttons to go forward and backward on the cycle. Going backwards to the scooping motion from the user would instead launch the food-gathering sequence.

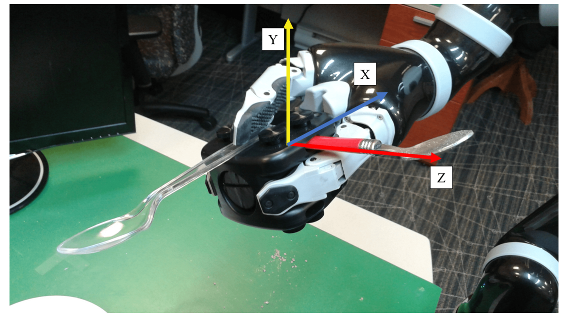

Fig. 3. JACO's dedicated small tool holder

TABLE I
Maximum number of bites taken per minute

Healthy person	JACO manual control	Feeding mode (excluding Regrouping)	Feeding mode (including re-grouping)
5-10 min^{-1}	0-4 min^{-1}	5-7 min^{-1}	3-5 min^{-1}

B. Implementation using a Jaco Robotic Arm

The feeding mode strategy described above was implemented on a Jaco robotic arm which is a wheelchair mounted assistive robot with 6 degrees of freedom. It has a wrist composed of two 60^o joints designed to avoid the possibility of jamming anything between the hand and the forearm which makes controlling motions about certain axis more complex. To simplify the implementation, we created a tool holder which holds one spoon for eating and another for the food-gathering trajectory, which are both aligned properly to be easily controlled by the last joint of the robot, as seen in Figure 3.

Using this tool holder and the feeding mode, we proceeded to compare the pace of eating of the mode to that of a healthy person as well as that of a user controlling the robot through its usual manual control input. The number of bites per minute was deemed a good metric for a qualitative comparison because the range in the pace of eating will vary a lot depending on a number of variables, such as the context of the meal or the type of food and personal habits, even for a healthy person. By limiting the measurement to 1 minute, the impact of these variables should be limited. It also encompasses both the scooping success rate as well as the motion velocity and efficiency.

As a benchmark, we measured the pace of eating of two healthy members of our research group. We also report the pace of eating using the manual control (via joystick) of JACO as reported by a user with upper limb physical limitations. Finally, we measured the pace of eating using our interface for the feeding mode. Each person was served 1.5 cup of oatmeal. The pace was acquired over the time required by each individual to finish eating the content of the plate. Oatmeal was used because it has a similar texture as other clumpy meals that are easier to eat for people with functional limitations. These results are summarized in Table I.

According to these results, we found that using the automated feeding mode allows a user to eat a normal meal under 30 minutes.

IV. Discussion and conclusion

We aimed to create a feeding mode for general-purpose assistive robots to allow users to eat a meal at a reasonable pace, with minimal effort and which offered enough flexibility to be used outside of the user's often heavily controlled home. In this section, we discuss the advantages and limitations of our motion planning and user interface as well as the results obtained from our implementation on JACO to assess our success. It is worth noting the value of having this kind of mode on a general purpose assistive robot rather than a specialized one. Assistive technologies are expensive, so having a single robot for multiple tasks is cheaper than having a specialized machine for every possible task. Moreover, one cannot expect users to carry all their specialized tools everywhere. General-purpose robots are simply more reliable in uncontrolled environments.

The scooping motion we propose can be performed from any direction and in any starting position in the workspace of the robot, thus offering unprecedented flexibility. This means that users could go to the restaurant, have their plate placed anywhere usual, find a configuration for their manipulator which reaches the plate with minimum nuisance to himself and his seating neighbours and proceed. This could not be achievable with a single-purpose assistive device which relies on a controlled environment.

The food regrouping motion was deemed adequate during our tests. By including this motion, the majority of a meal may be eaten. However, larger plates would require a more elaborate motion to perform properly. For example, successive food gathering trajectories could be performed with a gradually decreasing trajectory radius.

Our results regarding the pace of eating are not statistically significant given our small number of samples, but are only meant to be a demonstration of the usefulness of the scooping motion. We observed that even with an automated feeding mode, the pace of eating is still slower than that of a healthy person, but it is partly due to the fact that assistive robots are naturally slow for safety reasons. On the other hand, the automated feeding mode greatly improves the pace of eating compared to manual control of the robot, which could be so long it would be prohibitive to try eating with manual control. Moreover, given the simple user interface, the user is not required to apply his entire focus on the task of eating and may at the same time interact with other people, which makes eating a meal significantly more enjoyable.

The main limitation of the proposed automated feeding mode is that scooping is not an effective way for every kind of food to be picked up. Some type of food are more easily picked up using a fork, such as meat or lettuce, while other may require a more delicate motion with a spoon, such as soup. Trying to use our scooping motion with these types of food may result in a much lower scooping success rate.

We believe that the integration of a vision system, enabling the the robot to capture some information about its environment, could allow for an even smoother experience by removing the need for manually recording information about the environment, which takes time and effort for a typical user of assistive technology, and thus would improve further the meal-eating experience.

With the mathematical description of functional motions such as scooping, as presented in this paper, researchers will be able to more readily provide useful functionalities for assistive robots. The configuration-independent trajectory framework could be used to perform other useful functional tasks such as opening doors or shaving. The results of such work will empower users with more autonomy, improve their quality of life and reduce the burden put on caretakers.

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