Design of a Multiple-User Intelligent Feeding Robot for Elderly and Disabled

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

Signature

I understand that my thesis may be made electronically available to the public.

Signature

Abstract

The number of elderly people around the world is growing rapidly. This has led to an increase in the number of people who are seeking assistance and adequate service either at home or in long-term-care institutions to successfully accomplish their daily activities. Responding to these needs has been a burden to the health care system in terms of labour and associated costs and has motivated research in developing alternative services using new technologies.

Various intelligent, and non-intelligent, machines and robots have been developed to meet the needs of elderly and people with upper limb disabilities or dysfunctions in gaining independence in eating, which is one of the most frequent and time-consuming everyday tasks. However, in almost all cases, the proposed systems are designed only for the personal use of one individual and little effort to design a multiple-user feeding robot has been previously made. The feeding requirements of elderly in environments such as senior homes, where many elderly residents dine together at least three times per day, have not been extensively researched before.

The aim of this research was to develop a machine to feed multiple elderly people based on their characteristics and feeding needs, as determined through observations at a nursing home. Observations of the elderly during meal times have revealed that almost 40% of the population was totally dependent on nurses or caregivers to be fed. Most of those remaining, suffered from hand tremors, joint pain or lack of hand muscle strength, which made utensil manipulation and coordination very difficult and the eating process both messy and lengthy. In addition, more than 43% of the elderly were very slow in eating because of chewing and swallowing problems and most of the rest were slow in scooping and directing utensils toward their mouths. Consequently, one nurse could only respond to a maximum of two diners simultaneously. In order to manage the needs of all elderly diners, they required the assistance of additional staff members. The limited time allocated for each meal and the daily progression of the seniors' disabilities also made mealtime very challenging.

Based on the caregivers' opinion, many of the elderly in such environments can benefit from a machine capable of feeding multiple users simultaneously. Since eating is a slow procedure, the idle state of the robot during one user's chewing and swallowing time can be allotted for feeding another person who is sitting at the same table.

The observations and studies have resulted in the design of a food tray, and selection of an appropriate robot and applicable user interface. The proposed system uses a 6-DOF serial articulated robot in the center of a four-seat table along with a specifically designed food tray to feed one to four people. It employs a vision interface for food detection and recognition. Building the dynamic equations of the robotic system and simulation of the system were used to verify its dynamic behaviour before any prototyping and real-time testing.

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Dedication

This thesis is dedicated:

To my respectful, thoughtful parents,
my lovely, friendly siblings,
my supportive, well-beloved husband

and

To my happy, creative, energetic, bright, son
who, all, keep my spirit alive.

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Chapter 1

Introduction

The goal of this research was to design an intelligent robot, capable of simultaneously feeding multiple elderly or disabled people sitting at the same table. This feeding robot can be used in senior homes or similar places where people with upper-limb impairments often eat meals together.

The preliminary research for this project, started with exploration in the broad area of rehabilitation, with service and assistive robotics in general, for those with upper limb disabilities or dysfunctions. In addition to workstation robotics in places such as offices and hospitals, different types of assistive robotics systems were reviewed, including mobile and stationary, attached to and separate from the body, passively- and actively- controlled, and wheelchair- and table- mounted systems. This helped to determine the state of the art and potential benefits and problems of rehabilitation and feeding robots. The first intention was to come up with an assistive device for upper-limb disabled people that would benefit them in gaining independence in accomplishing daily activities. In the study, eating was found to be one of the most frequent and time consuming daily tasks, which would pose many social and emotional problems for the disabled. Since the elderly, as a population, have the most cases of upper-limb dysfunctions, the intention of the project was directed more towards developing an assistive feeding machine specifically for them. A parallel preliminary study aimed at the market analyses of the available feeding machines including their prices, success rates, features, constraints, and drawbacks was conducted; and knowledge about the demographics and conditions of potential and existing users of such assistive feeding devices was also acquired.

Consideration of some issues such as available resources, equipment and experience, made the choice of assistive robotic system more clear; a table-mounted, actively controlled, stationary robot, not to be used as an extender to any human body part, was ultimately decided upon as the focus of the design. It was also decided that the robot should be an intelligent one, with the ability to provide a more convenient and natural user-robot interaction than what is currently available. Since the eating task was found to be an activity of daily living (ADL) that is repeated more frequently and is more time-consuming during the week when compared to other daily tasks, the goal of the thesis was further refined as follows: to design an assistive robotic manipulator to make the elderly as independent as possible in feeding themselves. Therefore, the thesis literature review only reflects those devices or machines that assist disabled and/or elderly users with eating and drinking tasks.

It was found that the elderly and their feeding requirements in environments such as senior homes with many elderly residents dining together at least three times per day have not extensively been researched before. This, the unavailability of multiple-user feeding systems in the market, and the lack of related research motivated this project to focus on the design of multiple user feeding systems for nursing homes. The final decision to change the single-user feeding robot to a multiple-user device was made after a series of observations in an elderly behavioural reactions of the elderly during meal time in the nursing home, resolved many uncertainties regarding the real needs of this population in such places while feeding themselves. The user's characteristics and requirements as well as some information about the people and environment they were interacting with, such as caregivers and service-providers in dining areas, were grouped and considered all together. The outcome of assessing these observations both reinforced the idea about designing a multiple-users device and solidified the potential benefits of such an assistive machine to make the elderly more independent.

1.1 Objectives and scope

The objectives of this thesis are to:

1. Determine the end-user and caregiver needs and environmental factors that need to be considered in the design of a feeding system for elderly by conducting observations of seniors eating at a nursing home.
2. Perform a preliminary design of a robot system based on the results of the observations at the nursing home for elderly. The observations led to the initial design of a multiple-user feeding robot that includes:
    a) specifying the robot system and layout in the workspace,
    b) determining robot tasks required and their management for multiple users,
    c) performing motion planning of the robot system to determine the robot joint angles based on the end-effector position,
    d) performing image processing for motion planning and task execution.

The layout of this thesis is as follows: Chapter 2 presents a literature review of previous and current research attempts to design an assisting device to help the elderly or disabled with feeding themselves; it also analyzes the existing market and reviews the available user interfaces utilized by feeding machines or similar rehabilitation or service robots. Chapter 3 reveals the objectives and results of a series of observations in a nursing home. The listed characteristics of the typical users and specifications of the desired robot are based on the outcomes of these observations. Chapter 4 introduces the design of a feeding robot, including a robot manipulator and food trays and their dimensions. Chapter 5 reviews the kinematic, dynamic and control issues of the proposed feeding robot. It assigns the coordinate systems, defines Denavit-Hartenberg (DH) parameters and tables, calculates the transformation matrices for each joint and finds the Jacobian matrix and singular positions. The inverse kinematic analysis is provided along with the preliminary steps for controlling the robot using ADAMS software. Chapter 6 explains the vision system and image processing for recognition of some types of food inside the tray. This chapter shows the results of processed images by the developed algorithm for segmentation of the pieces of solid foods inside the food tray and finding the best insertion point for the fork. Finally, Chapter 7 concludes the project and highlights plausible future directions of research that would complement the present study.

Chapter 2

Literature Review

The most important goals of this chapter are to review previous and current research attempts to design assistive feeding devices and their user interfaces, and to perform a market analysis by introducing similar products available in the existing market for use by elderly and disabled people with any kind of upper-limb dysfunction. However, before presenting such a review, the issues of a rapidly increasing elderly population, the escalating problem of their required personal and public services, and different kinds of diseases which may lead to disabilities of upper-extremities are discussed. This discussion will reflect the importance of designing assistive machines, rehabilitation or service robotic systems for this population to use in different environments.

One of the important issues in designing assistive devices is laid on the demographics of their users. The statistical data regarding the number and characteristics of the user population plays an important role in motivating the continuation of such projects, as well as determining the design limitations to be considered and necessary features to be added to the system. The next section introduces the objectives of the market analysis for the feeding device and lists important issues that will be discussed in the next sections.

2.1 Marketing

The objective of marketing is to understand both the market itself and the requirements of consumers in order to be able to identify the design constraints of the proposed product and its price. In rehabilitation and service robotics, many good designs have failed because of basic design flaws, such as cost, ergonomics and difficulties in utilizing controls. Therefore, it is critical for a designer to determine the user requirements as well as the design limitations beforehand.

One of the most important parts of analyzing the market for an assistive feeding device is the needs analysis. The needs analysis looks at the statistics and studies about the people who are in need of such devices. Furthermore, major criteria such as age, type of disability, gender and income level of the users are important in the design considerations; and the priorities may be different based on whether the user lives in an institution, with a family member, or independently with a caregiver to assist in the activities of daily living (ADL).

Some of the issues to be discussed in the upcoming sections of this chapter are: 1) the number and characteristics of people in need of assistive devices (demographics of the potential users), 2) the demographics of existing consumers of available products (existing user demographics), 3) causes of upper limb disabilities of the users and consequent dysfunctions in ADL, specifically with respect to the elderly, 4) physical and mental capacity of the consumers to operate the device, 5) available assistive devices in the market for people with difficulties using any part of their upper-extremities, 6) previous and current related research projects that have been attempted or reached completion, 7) features, constraints and prices of available products and useful applicable information; and results from previous and existing research relevant to this project, 8) available user interfaces specifically for feeding devices and similar rehabilitation devices in general.

Since the majority of the potential users of the proposed feeding system are elderly, 65 years of age or older, the following section attempts to convey the fast growing problems of aging for today and the future.

2.2 Aging Population and Escalation of Required Services

Older adults are the fastest growing group in North America, Europe, and Asia [1]. As demonstrated in Table 2-1 [2], which shows the number of Canadians over age 65 as a percentage of the total population, by 2016, almost 16% of all Canadians will be aged 65 and over. In addition, Figure 2-1 [4] demonstrates the increasingly fast rate of growth expected of the Canadian elderly population in the future compared to just a few years ago. The United States also expects a dramatic increase both in number and proportion of the elderly population [3]. The rate of occurrence of disabilities increases as age increases, which means that as people get older they are less active and need more assistance. Canada has the highest rate of institutionalization of elderly citizens in the world [5]. Almost 10% of Canadians over the age of 65 are living in long-term care institutions because they can no longer safely care for themselves. The increasing number of elderly people in conjunction with the increasing frequency of their disabilities will have a big impact on the future of healthcare systems, as it will be necessary for them to make adjustments in order to provide adequate services for this population. The next section will discuss some aspects that affect the required services of elderly people.

Table 2-1: Aging demographics from 1998 to 2041 in Canada [2]

Year	**Number**	**Population share**
1998	3.7 million	12.3 %
2016	5.9 million	15.9 %
2021	6.9 million	17.8 %
2041	9.7 million	22.6 %

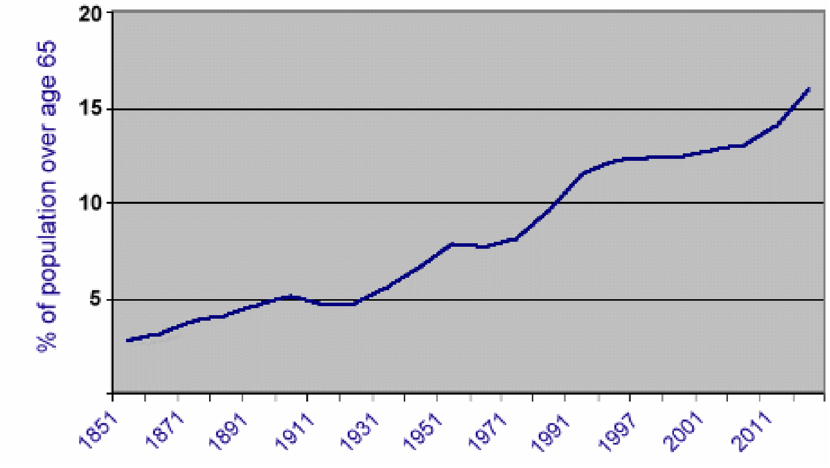

Figure 2-1: Canada's Aging Population [4].

The focus of most national aging policies is on dignity, independence, participation, fairness and security [6], since the quality of life of the elderly is very important. Consequently, older adults require a huge share of special services and public support. The number of persons requiring formal care (mainly nursing home care) and informal care (mainly care at home) will increase sharply even if the proportion of persons at each age remains unchanged.

Another issue that will affect providing the necessary services for the elderly is the number of available nurses and caregivers. A study about the workforce of aging registered nurses [7] reveals that: a) within 10 years, 40 percent of working registered nurses (RNs) will be 50 years or older; and b) as those RNs retire, the supply of working RNs is projected to be 20 percent below requirements by the year 2020. This shortage of employed nurses and caregivers in the coming years will provide significant opportunities for robotics and artificial intelligence (AI) researchers to develop assistive technology that can improve the quality of life for the aging population. [8]

2.3 Self-Feeding Disabilities

In order to assess the demographics that would benefit from assistive devices, specifically for feeding, one would typically look to the statistical data available for populations with disabilities in general and the elderly specifically. Unfortunately, there is great variation in the incidence of disabilities in the statistics from different countries. These differences may be caused by different reporting criteria, degrees of industrialization, rate of accidents, or participation in wars. Statistics for senior populations seem to be more telling, as the proportion of seniors in the general population of developed countries is higher than in underdeveloped countries. Also, almost 75% of the elderly (aged 65 and over) have at least one chronic illness and 50% have at least two chronic illnesses [9]. Chronic conditions can lead to severe and immediate disabilities, as well as progressive disabilities that slowly erode the ability of elderly people to care for themselves [10].

In general, some of the neuromuscular diseases which cause any disability or dysfunction in the upper-extremities may hinder the typically easy procedure of eating or make it a very difficult task to accomplish. The disabilities that lead to upper-limb disabilities are: Essential Tremor, Parkinson, Dementia/Alzheimer, Stroke, Spinal Cord Injury (SCI), Multiple Sclerosis (MS), Cerebral Palsy (CP), Spinal Muscular Atrophy[1] (SMA), Muscular Dystrophy (MD) and Amyotrophic Lateral Sclerosis (ALS) [11]. But among these, the first four are more common among the elderly.

Those with essential tremors [12] have difficulty eating normally or holding a cup or glass without spilling it, and if the voice or tongue is affected, difficulty in talking may occur. Parkinson [11], [12] which affects muscle movement nerve cells, causes tremors of the fingers and arms, muscle rigidity in the limbs and neck, slowed motion, impaired speech, loss of automatic movement, difficulty chewing and swallowing and also problems with movement balance and coordination. Dementia and Alzheimer's disease [11], [12] can cause a decline in memory, comprehension, learning capability, and ability to think, as well as language and judgment. People suffering from this kind of disease may see food on their plate, but they cannot logically connect hunger to food to feeding.

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[1] Atrophy: A wasting of a part of the body because of disease or lack of use. [Wikipedia Encyclopedia]

Furthermore, people with SCI may have tingling or loss of sensation in their hands, fingers, feet, or toes; partial or complete loss of control over any part of the body; and difficulty with balance. Those with MS may experience coordination and memory problems, blurred vision, muscle spasticity, indistinct speech, tremor, weakness and swallowing disorders. MD, on the other hand, is a muscle disorder that causes weakness and wasting of the voluntary muscles that are responsible for movement of body parts. Similarly ALS is a disease of the motor nerve cells in the brain and spinal cord that causes those afflicted with it to have muscle weakness, twitching, cramping and stiffness of muscles, slurred speech, and difficulty chewing or swallowing.

In general, an elderly person with limitations of vision, hearing or mobility can be made more independent if the deficits are properly assessed and the environment appropriately designed. The prevalence of sensory changes and injuries among the elderly dictates the importance of addressing them in primary care settings. The elderly individual's perception of the environment changes subtly as the senses age. Changes in vision, hearing, taste and smell are almost universal. Only 5% of persons over 80 have 20/20 vision, and nearly 60% of those aged 65 to 70 show evidence of cataracts or glaucoma. Twenty-five percent of those over 65 have some type of hearing problem and among persons over 75, the incidence increases to over 40%. Sixteen percent of the elderly report they can hear only shouted speech. Similarly, the thresholds for taste and smell increase with age [12].

Lower frequency, lower pitch and tone of voices, an increase in sound threshold, especially for high-pitched sounds, a decrease in speech discrimination and auditory judgment are some of the typical characteristics of the elderly group. They are also more susceptible to eye diseases and having vision problems [4]. They usually have difficulty in reading small print; have poor vision in environments with insufficient light and need longer adaptation time to light changes.

Sensory losses, especially for the older population, limit self-care and activities of daily living, and significantly alter communication and interaction patterns [4]. Impairment of the senses contributes considerably to the decline in functional state of the elderly individual and leads to their increasing isolation. The sensory impairments of the elderly, such as partial to complete loss of the ability to hear, talk, or see will have the effect of decreasing their functionality in conducting everyday tasks. The above analysis makes clear that, as with any new technology, it is important to consider the characteristics of the users who will benefit from it before designing a new assistive device. Indeed, the proportion of seniors with upper extremity disabilities, the cause of and physical manifestations of those disabilities, as well as the natural degradation of sensory perception that may alter the functional abilities of the elderly are all important considerations in the design of an assistive eating robot.

2.4 Eating As a Daily Activity

Among the total everyday obligatory activities for the elderly, eating is the most time consuming. Based on the study of Moss and Lawton in 1982 [13], the mean minutes spent eating in a 24-hour day for impaired residents averaging in age from 75.2 to 79 was 77 minutes, whereas the time spent for other daily tasks such as personal care or health care, shopping, housework or home maintenance, and cooking was noticeably less (see Table 2-2 for the average time spent on typical daily tasks by the elderly). It is obvious from Table 2-2 that having any difficulty in accomplishing eating tasks will have a great impact on the social behaviour of elderly individuals.

Table 2-2: The mean minutes spent for daily activities of elderly with average age of 75.2 -79 [13].

Daily Task	**Spent Time (Minute) for Impaired Residents**
Eating	77
Shopping	22
Personal/Health care	71
Housework/ Home maintenance	68
Cooking	69

The next section introduces different types of assistive feeding devices which are either manufactured and available in the market, or are still in the research phase and have only been designed or prototyped.

2.5 Available Feeding Devices

Currently, the numbers of research areas that are finding ways to support those with upper limb disabilities to independently accomplish their various activities of daily living (ADL)- are growing. One part of this vast research area is focused on providing facilities for eating and drinking, preparing food, going to the bathroom, bathing, and getting dressed. These assistive devices have the potential to not only increase self-esteem, confidence in accomplishing ADL tasks and independence, but also to decrease the number of caregivers and institutional costs required to adequately care for this population.

The desire to assist in feeding those with upper limb disabilities or dysfunctions with a machine or robot, in an effort to help them accomplish their eating tasks independently, has been capturing the minds of many researchers and designers for decades. Whether the devices are simple mechanical or electromechanical machines or complicated, intelligent robots, gaining independence in ADL has been the major motivation behind their development.

Using different human–machine interfaces, from simple switches activated by different body parts (depending on type of disability), to more advanced ones, such as voice and speech recognition and synthesis, laser pointing devices, object recognition and computer vision, researchers have tried their best to accommodate the needs of users, patients, and elderly persons who have expressed the desire for an assistive device that not only helps them eat more easily and neatly, but is both safe and comfortable to use, and will allow them to minimize their dependence on nurses, caregivers or family members. Some of the proposed and commercially available assistive feeding systems will be mentioned in the following sections. These devices have been categorized as: arm supports, human extenders, electro-mechanical devices, and intelligent automatic or semi-automatic machines.

2.5.1 Arm Supports

Action Arm: Action Arm, distributed by Flaghouse Inc. [14], is designed for use by individuals with neurological or upper extremity disabilities or spinal cord injuries. This device, shown in Figure 2-2 (a), includes multiple joints, like the human arm, that provide a variable repetition and kinesthetic feedback (feedback that helps to detect bodily position, weight, or movement of the muscles, tendons and joints). The unit, which has a flexible mounting system, is equipped with an adjustable resistance and range of motion, and a stylus (sharp, pointed tool) that can adjust to hold writing or eating utensils.

Friction Feeder: Friction Feeder [15] is made for users suffering from spasticity (having involuntary contraction of a muscle or group of muscles), mild tremors, ataxia (loss of the ability to coordinate muscular movement) or mild-to-moderate uncoordination.


(a) (b)

Figure 2-2: (a) Action Arm [14], (b) Friction Feeder [15].

It helps in leading any inappropriate movement of the shoulder and elbow to the correct direction, and assists in self-feeding and leisure activities. Bands are used to aid control of horizontal shoulder abduction (drawing away from the midline of the body) and adduction (drawing inward toward the median axis of the body), and flexion and extension of the elbow. (Figure 2-2(b))

Ball Bearing Feeder with Elevating Proximal Arm: The Ball Bearing Feeder [15] is a balanced forearm orthosis designed as an arm support for feeding those with shoulder weakness. The device, which can be clamped to most wheelchairs, consists of a metal arm trough with free swinging arm support and a ball bearing joint.

Stable Self Feeding Support: Stable Self Feeding Support [15], represented in Figure 2-3(a), guides the arm as it moves from plate to mouth. It provides a support for the forearm and allows it to move into the smaller top section with a simple sliding motion. This gives stability and support, while bringing food to the mouth. The roof attachment helps to keep the arm on the slide and provides additional control and support.

Comfy Feeder: Comfy Feeder [15, 16] helps individuals with Multiple Sclerosis, Parkinson’s disease, Cerebral Palsy, other neurological conditions, and those with generalized upper extremity weakness, feed themselves by allowing them to guide an attached spoon through a food-pick-up sequence. A gas-spring level damper absorbs tremors and jerky movements; and the self-levelled spoon eliminates messy spills and ensures horizontal positioning from the bowl/dish to mouth. The spoon and pivot assembly, shown in Figure 2-3(b), can be attached to operate either in, or at a right angle to the plane of the arm. It has a rotating platform on a non-slip baseboard. Since the user only controls the eating process, no external power source is used.

(a) (b)

Figure 2-3: (a) Stable Self Feeding Support [15], (b) Comfy Feeder [15].

Stable Slide: Stable slide [17] is an arm support designed to provide support during the activity of self feeding for individuals with tremors, limited strength, or motor control disabilities. The portable device can be clamped to tables, is fully adjustable both in height and angle, and is available for both right and left handed individuals. Since it doesn't have the ability to move the user's arm, it is not appropriate for those with paralysis or severe weakness.

The next section introduces assistive feeding devices called teletheses, which attach to a human body part, such as the head, leg or foot. They are passive mechanisms that act as an extension of the person and rely on the remnant functional musculature of the coupled body part to transform its motion into a usable motion of an end effector such as a spoon or fork. These mechanisms take advantage of extended physiological proprioception (EPP)[2] to use direct feedback control from the users to operate the simple device with flexibility and reliability [18].

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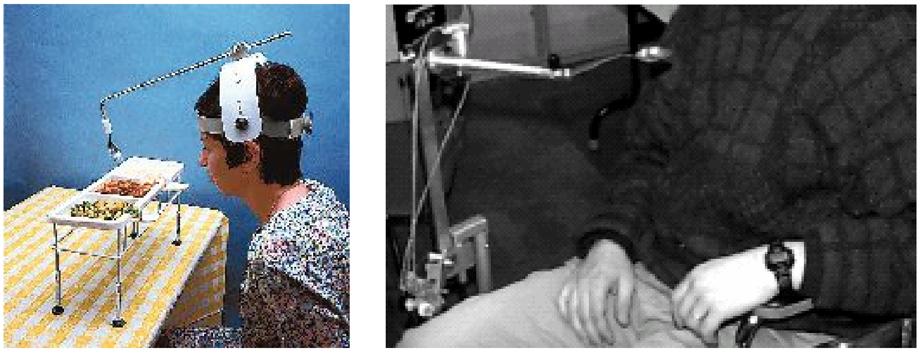
[2] EPP: Extended Physiological Proprioception describes the ability to perceive at the tip of the tool such as a human extender or a prosthetic limb. {Wikipedia Encyclopedia}

2.5.2 Human Extenders for Feeding

Eatery: Eatery, manufactured by Do It Yourself and available at Maddak Inc [19], is a non-articulated device that allows bilateral upper-limb amputees to eat independently without prostheses. The plastic tray has three compartments and a height adjustable plastic-coated stand. The front of the tray, as shown in Figure 2-4(a), has two spoon-like projections; and the user uses their mouth to directly take food off the tray at this projection by use of the head piece. The device requires the user to have some trunk movement and good head control, which is a limitation since people with neck or spinal cord injuries may not be able to benefit from it. However, these simple devices would be ideal for non-prosthesis users that are in otherwise good physical condition. The lightweight headpiece is adjustable and padded for a comfortable fit. The modified spoon and plastic tray are removable. The headpiece can be used as a pointer if the spoon attachment rod is replaced with a head pointer rod.

Magpie: Magpie [21], represented in Figure 2-4(b), is a purely mechanical, leg operated, wheelchair-mounted, low cost, assistive device which is designed and manufactured at the Nuffield Orthopaedic Center in Oxford, England. It can help users not only with feeding, but with other tasks such as typing, turning pages, and shaving. It has the advantage of providing the user with continuous feedback by virtue of the direct coupling of the end effector of the feeding device and the human joints (human legs in the case of Magpie). Its limitation is that it can only be used for those who are able to move their legs but not their arms. Therefore, people with spinal cord injuries would be unable to benefit from it, since they are often unable to move their legs as well as their hands.



(a) (b)

Figure 2-4: (a) Eatery [20], (b) Magpie assists in eating [21].

HAND Feeder: Head Actuated Nutritional Device (HAND) [21] is a passive, head-controlled feeding device for quadriplegics. The mechanism, shown in Figure 2-5, is like a telethesis, coupled to the user's body part and acting as an extension of the person. The virtual model of the feeding mechanism, developed at the University of Pennsylvania, is shown in Figure 2-8. This 3-DOF passive mechanical feeder driven by cables uses head and neck movements to control the movement of a spoon. The head yaw movement causes the linkage to rotate about a vertical axis and translate in a horizontal plane to keep the spoon in the line of sight of the user.

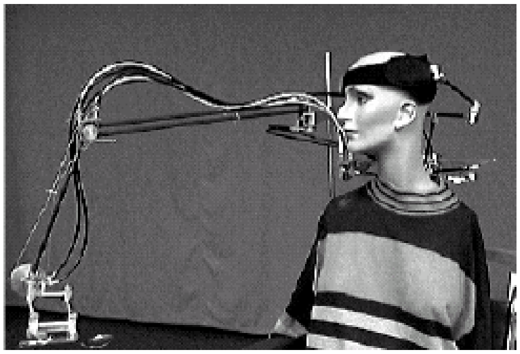


Figure 2-5: HAND Feeder [21].

The head pitch movement causes the spoon to perform a planar motion that involves scooping up the food and bringing it up to the mouth. The head roll movement causes the spoon to pitch about a transverse axis [21]. It transforms the user's head motion into a usable motion of the end effector such. One of the limitations is that it can only be used by those quadriplegics who have control of their neck. It also consists of a 6-DOF user input subsystem and a 3-DOF end-effector subsystem, which makes it very bulky for individual use and requires considerable of space.

The following section introduces the electro-mechanically powered devices that use an electrical power supply to activate the machine.

2.5.3 Electro-Mechanical Powered Devices

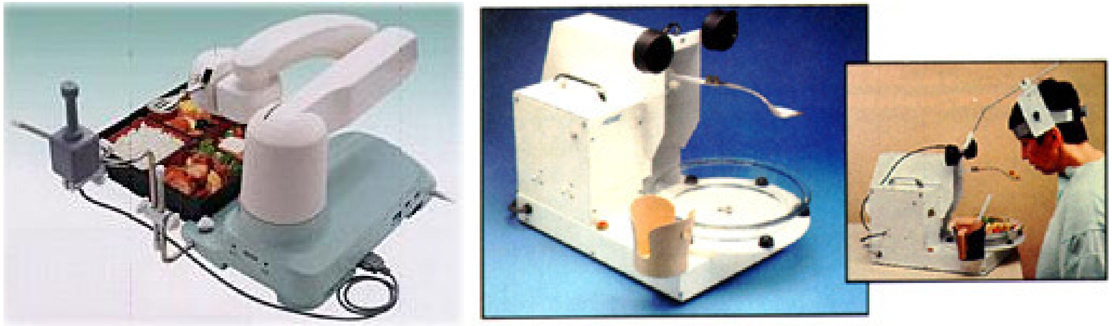
University of Illinois Feeding Mechanism: The feeding mechanism developed at the University of Illinois (Urban-Champaign) was custom designed for a student with physical and mental disabilities.

It used a Compact Carriage Mechanism (CCM), utilizing the interaction of three shafts, three tension springs, a rotational damper, and two cams to produce the optimum motion of the utensil. The device consisted of a mechanism enclosed within a PVC case, a spoon that is detachable for cleaning, a specially designed bowl, a pad switch for user input and a 12V DC power supply that plugs into a wall outlet. The device was not commercialized and the spoon had limited degrees of freedom. [22].

My Spoon: My Spoon, manufactured at Secom Co Ltd [23], is a powered feeder designed for use by individuals with spinal cord injury, upper extremity disabilities, or amputation, which allows users to eat most types of everyday food with minimal help from a caregiver. A base unit, shown in Figure 2-6(a), sits on the table next to a dish with four compartments. The device can operate in manual, semi-automatic, or automatic modes, with a joystick, button switch, or combination of joystick, button or switch controller.

There is no vision system for food recognition. Therefore, it is the user's responsibility to choose the desired food and direct the arm, by interacting with the machine through a laser pointing system. The user operates the robot only by head movement to point on the up/down/right/left/back and forth buttons on the panel to move the robot arm in the required location and orientation. After the food is removed from the spoon, the robot arm returns to the home-position automatically. Application of the non-contact sensor and emergency switch did not work on this device for safety reasons, because of low reliability of the sensor in defending the user and inability of a disabled person to quickly operate the emergency switch. However it has been stated in [24] that the light weight of the robot arm and its low speed ensures the safety of the user.

Beeson Feeder: Beeson Feeder from Maddak Inc [19], shown in Figure 2-6 (b), is for persons with severe physical or cognitive limitations due to cerebral palsy, SCI, or other impairment involving movement, coordination, or range of motion. One control operates a spoon to take food to the mouth level and the other one rotates the plate to keep the food properly distributed for the spoon to pick up. The user should be cognitively aware of the cause and effect of the two-switch operation, have two consistent points of motor control for switch activation, and the ability to move the body or head forward to take food off the spoon.



(a) (b)

Figure 2-6: My Spoon [23], Beeson Feeder [19].

Neater Eater: Neater Eater from Therafin Corporation [25], shown in Figure 2-7, is a powered feeder with programmable arm. The device can be set up for five different diners, but only one diner can utilize it at a time, and the automatic cycle of the spoon can be controlled in four different ways. The user can control the spoon or plate cycle with one or two switches that can be pressed with the hand or knee. It keeps the spoon level as the arm is moved. In a manual version, adjustable springs help the user to smoothly guide the spoon down into the plate, and back up to the mouth. Adjustable stops prevent the spoon from moving past the plate or too close to the user, and stop the spoon at the right height for the user's mouth. In an adapted version, the adjustable handle allows the spoon to be used with relatively small movement of the user's hands. A plate-turner wheel allows the user to turn the plate without lifting their hand from their lap. Tall spacers underneath the base help to reduce the distance the spoon has to travel from the plate to the user's mouth.

Figure 2-7: Neater Eater [26].

Assistive Dining Device: Assistive Dinning Device from Mealtime Partners Inc [27] is a powered feeder that has rotating bowls, a mechanical spoon, and a positioning arm. The bowls rotate until the desired food is located under the spoon. To avoid mixing, each food is contained within a single bowl. (Figure 2-8) It can hold up to three bowls of food at one time, each of which holds one cup. Three general modes of operation are: 1) fully automatic, 2) using one adaptive switch, and 3) using two adaptive switches. The feeder can be set to operate with numerous combinations of rotational speed, length of time the device pauses to allow the user to take food from the spoon, minimum dwell times for the switches, and time settings for spoon retraction after user contact. The operation is done with the help of a control panel.

Figure 2-8: Assistive Dinning Device [28].

Winsford Feeder: The Winsford feeder [31], shown in Figure 2-9, is a single-purpose feeding aid which enables individuals to feed themselves independently from a standard dinner plate or bowl. It is controlled by either a chin switch or other types of switches. The height of the feeder may be adjusted, but the user should have stable head and trunk control. Food preparation and feeder setup is performed by an attendant.

A rotating plate lets the user pick up food from any location on the plate by the help of a pusher for placing the food on the spoon. If the amount of food is too little, the plate and pusher may be activated again to add more food to the spoon; and if it is too much, it may be returned to the plate and emptied. A cup holder is included to hold drinks that are normally accessed with a straw; and a drip pan and shelf prevents food from spilling on the user.

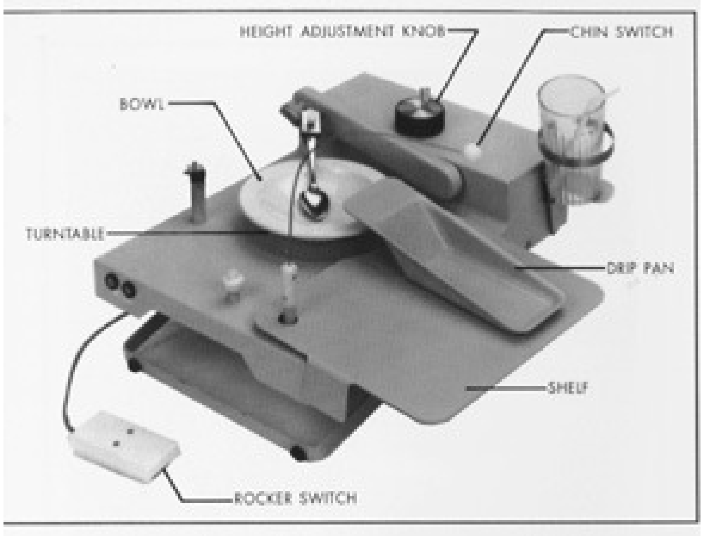


Figure 2-9: Winsford feeder [31].

Automatic Feeding Device: The automatic feeding device from Sammons Preston Rolyan [18] is a battery operated feeder. The speed and sequence of operation is controlled by a chin switch. It has some features such as an adjustable height stand, spring supported spoon and remote switch for the hand or foot, but it requires sufficient head control to push the switch and to position the mouth at the spoon location.

Electric Self-Feeder: The electric self-feeder, made at Sammons Preston Rolyan [15], is a battery-powered feeder which assists disabled people in eating meals at their own speed. A slight head motion on the chin switch activates the motorized pusher to fill the spoon and then automatically moves it to the mouth. The rotation of the plate is controlled for food selection. A bowl may be substituted for the plate by removing the plate and pusher and adding the turntable, shelf, and drip pan. The height can be adjusted. The feeder includes a removable hand or foot control for individuals who are unable to operate the chin switch.

Mila One-Step Electrical Feeder: The Mila Electric Feeder, manufactured by Mila Medical Company [29] and shown in Figure 2-10, is activated by hand, arm, shoulder or head in one simple motion. By pushing the padded bar, it lowers a spoon to scoop food while a plate mechanically rotates to a new position. The base, push bar, and aluminium bar support a detachable spoon, plate and cup holder. This simple device needs the least physical control and can be activated by one’s head or other parts of the body to scoop the food and automatically rotate the plate. It is adaptable to both adult and children sizes and also various types of disabilities. The users have complete control and can eat at their own speed. One of the limitations of the device is its dependency on a power supply.

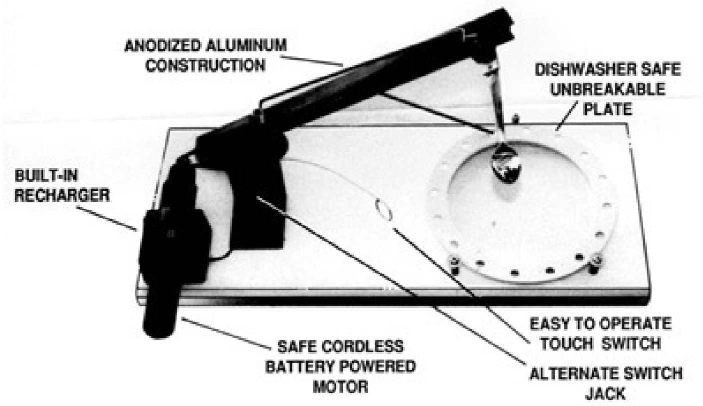


Figure 2-10: Mila Feeder [30].

More advances in robotic related technology and also the limited control of the user over the machine in electro-mechanical feeders led the designer to develop a more intelligent assistive feeding system [32]. Although there are many commercially available non-intelligent feeding devices, the intelligent systems are mostly in the research state.

The following section introduces some of the robotic feeding systems which are mostly articulated serial manipulators, fully automatic and actively controlled. Some of them use an intelligent user interface, such as vision system, speech recognition or speech synthesis, to provide more autonomy for the users.

2.5.4 Assistive Robotic Feeding Systems

Robotic Feeding Device for Quadriplegics: A robotic feeding device for quadriplegics [33] was designed at the University of Alberta, Canada in 1983. It was a programmable robotic arm, with 5 revolute joints and 5 motors in each joint, and was designed specifically for feeding the severely disabled. The cost of mechanical parts and transducers was claimed to be reduced by using the device in learning mode, by manually forcing it through the desired motion and also utilizing the transducers to track the motion. The electromechanical driving devices were used as angular displacement transducers. The motor can only be used as either a motor or as a measuring transducer at one time. This was one of the system's drawbacks.

Handy 1: Handy 1 [34, 35] was one of the early approaches (1987) to an intelligent eating assistant system (not attached to the wheelchair) that has also been successful in the marketplace. Since then, people with cerebral palsy, motor neuron disease, multiple sclerosis, stroke and also the elderly have benefited from this assistive device. (Figure 2-11)

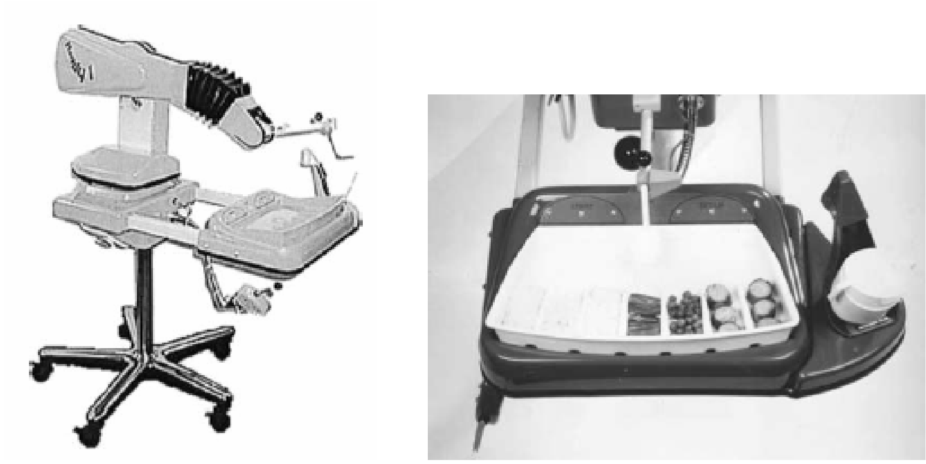


Figure 2-11: Handy 1 overall system and food tray [35].

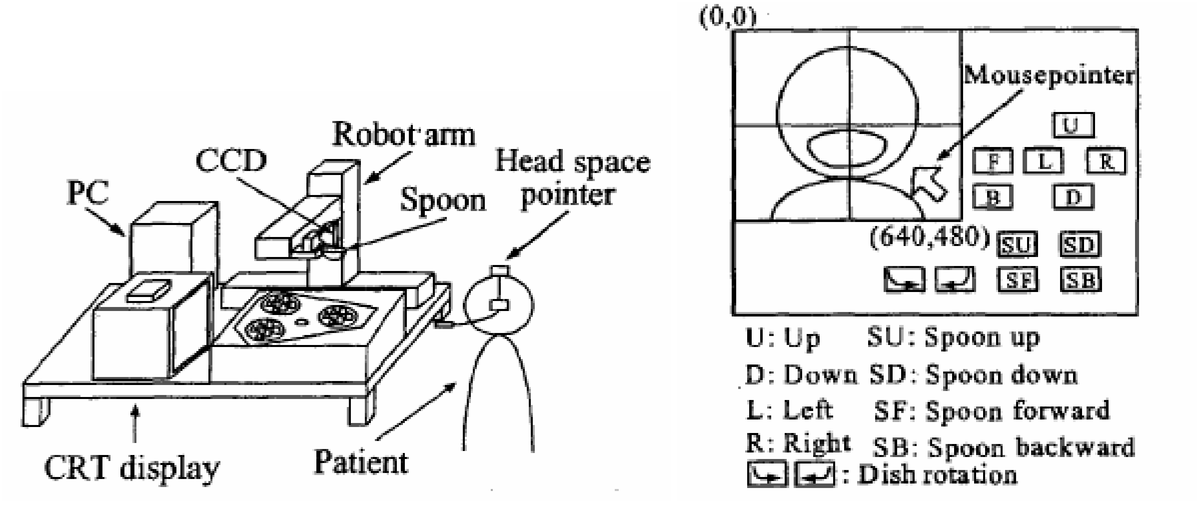
The ease of use, requiring only a slight touch from the user in order to operate the system, low cost and aesthetically pleasing appearance have made it successful. It helps the user not only in eating and drinking, but also in washing, brushing their teeth and make up application for women. The eating and drinking system consists of a scanning system of lights that allows the user to select food from any part of the dish. The user waits for the light to scan behind the desired column of food and then presses the single switch which sets the Handy 1 in motion. Two years later, a unique input/output board was designed to slot into the PC controller which incorporates capabilities for voice recognition, speech synthesis, inputs for sensors, joystick control and stepper motor drivers, to ensure that the design could be easily upgradeable for future developments [35].

ISAC (Intelligent Soft Arm Control): ISAC [36- 38], from the Center of Intelligent Systems in Vanderbilt University (1991), used a vision system and speech recognition to interact with the elderly through natural commands [36]. The system, shown in Figure 2-12, contained a 5-DOF manipulator which was pneumatically controlled by a microprocessor-based controller. It benefited from Rubbertuator, which was a pneumatic actuator that operated in a manner resembling human muscle. It was light weight, had a high power-to-weight ratio and had inherent compliance control characteristics [37].

Figure 2-12: ISAC at work [38].

The system was equipped with three CCD cameras, one located on top of the table for monitoring the food and two in front and side of the user to monitor the user's face. An image processing board could capture images from up to four CCD cameras. The control software was distributed among several workstations interconnected through an Ethernet LAN. For safety reasons, a collision avoidance subsystem was added to the whole system by utilizing real-time face tracking and motion prediction and reactive/predictive motion planning. Face tracking planned the approach path to the face and helped in collision prediction/ detection. Motion prediction was added to enhance the performance of the face tracking system and also for collision avoidance. Considering the fact that this robot arm could feed only one individual person, it was very bulky and required considerable space.

Eater Assist: Eater Assist [39- 41], from Kanagawa Institute of Technology, Japan, utilized a Cartesian robot to handle, move, rotate, and withdraw a spoon. With a head space pointer and personal computer display the user could control and operate the system with either head movement, blowing into a tube or by selecting direction/location commands listed on the PC display located in front of them. The system provides two options to the users to move the robot arm on CRT (Cathode-Ray Tube) display. One is the use of various defined icons on a CRT display that has been assigned to a specific movement of the arm, for instance the letter U for upward movement. The other is the use of an image from the CCD camera. In the example shown in Figure 2-13(b), the robot is moving towards the specified point on the picture (such as mouth).



(a) (b)

Figure 2-13: (a) The concept of Eater Assist robot, (b) CRT display [41].

Assistive Robot for Bedridden Elderly: The Kanagawa Inst. came up with another assistive device that is used for bedridden elderly people to help them with handling drinking cups, and picking up their belongings from unreachable locations. The user would use the laser pointing device to communicate with the robot. [42,43]. As shown Figure 2-14, the robot is a Cartesian robot with a hanging arm above user's head that can move toward the specified object location selected by a laser pointing device.

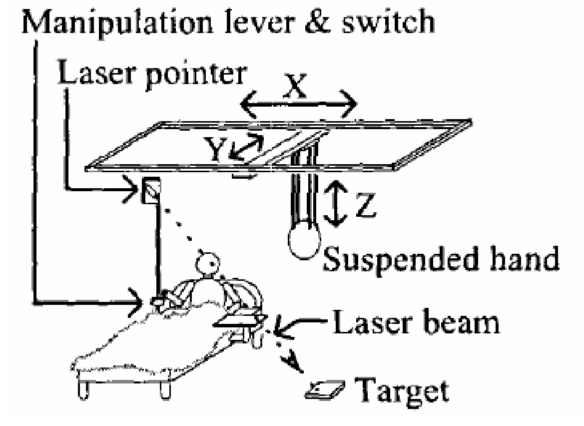


Figure 2-14: Assistive Robot for Bedridden Elderly [43].

Assistive Robot Hand: A robot hand, designed at Yamaguchi University, Japan [44], is a 5-DOF robot with a vision system to recognize and detect the positions of dishes, cups and utensils (Figure 2-15). It includes speech synthesis and recognition software for bilateral communication in case of image processing failure. Some of the limitations of the proposed system are based on assumptions about the users and environment that do not work properly in public situations or for users with limited speaking and hearing abilities. That is, for this system it is assumed that the user can speak well enough to select some simple commands. Also, the reconfirmation process is cumbersome.

Every time the recognition process is done for every object, the system reconfirms the recognition result with the user by asking if this is the object (for instance the first dish) and then waits for “yes” or “no” answer. It does this for all of the existing feeding utensils on the table. If the position of the object is not right, it also asks how it can be corrected. This method of communication between the robot and user is absolutely useless for locations where many people are dining together and the abilities of the user to provide a clear and recognizable voice is limited.

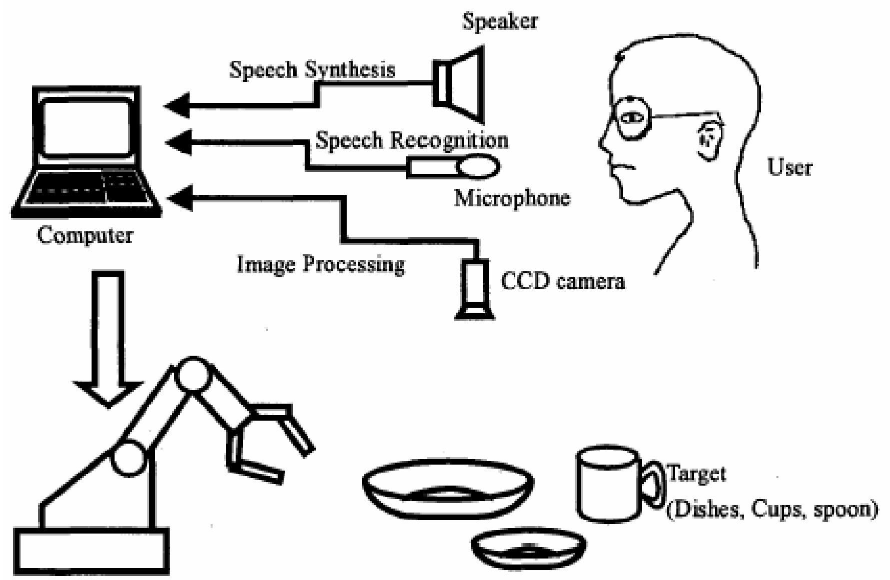


Figure 2-15: Configuration of Assistive Robot Hand system [44].

Although the reconfirmation process for each object and vocal command may increase the accuracy of results, it also significantly increases the time taken to complete a task. This time may exceed the patience of users when they are hungry. In addition, no strategy has been specified to handle the task of using a fork as a utensil for picking up the food.

Food Tray Carry Robot: People with difficulty in moving their arms can actuate the Food Tray Carry Robot [45] with very little force applied by a finger. The robot arm is a lightweight manipulator, set on the floor beside the patient's bed.

Strain gauges installed in a man-machine interface that is attached to the robot's tip, can detect the force applied to the operation plate. The parallel link system in the radial direction has been used to keep the food tray even with the ground. Therefore, no actuator or control system is required to maintain the horizontal plane of the food tray.

The next section lists the prices of some of the previously mentioned feeding devices that have made it to the marketplace. Prices are not available for all of the aforementioned devices, largely because some have not yet been commercialized and others are still in the research phase of production.

2.5.5 Prices of Feeding Devices

The costs of some of the available non-intelligent feeding devices are presented in Table 2-3.

Table 2-3: Prices of the available feeding devices in the market.

Feeding Assistive Device	**Price**
Action arm [14]	$149.00 (US)
Assistive dinning device [28]	$7995.00 (US)
Mila One-Step Electrical Feeder [46]	$300.00 (US)
Friction Feeder[15]	$473.95 (US)
Comfy Feeder [15,16]	$510.95 (US)
Neater Eater Manual Version [25,26]	$2,149.95 (US)
Neater Eater Electric Version [25,26]	$ 3,795.95 (US)
Neater Eater Adapted Model (Left or right hand) [25,26]	$2,695.95
Magpie [46]	$1,750.00(1987)
Winsford Feeder [15]	$3,745.95 (US)
Handy 1 [34, 35]	£3950.00 (UK) (1996)

2.5.6 Discussion on Feeding Devices

The review of different available feeding devices reveals that most of them are specifically designed for the purpose of home use by one individual person. There was no multiple-user feeding device available in the market. The complete review also reveals that attention has not been paid to environments outside the home either in the market or in research. The importance of environments such as senior homes for the elderly and their consequent difficulties motivated this idea of designing a special feeder for people in this environment.

The next section introduces some of the input and output devices and methods for sending commands to the machine and releasing information to the users, respectively. Then the appropriateness of each, with respect to its use in feeding devices, mostly for the elderly, and in public dining areas such as senior homes, is discussed.

2.6 User Interfaces for Feeding Devices

An important factor to determine the success or acceptability of a service robot relates to the physiological aspects of implementing techniques for human-robot interactions in unprotected and unstructured environments [47]. Discussed in this section are possible robot interface devices that can be applied in a dining environment in a way that can be beneficial for people with upper-limb disabilities or dysfunctions. A user interface makes it possible for users to interact with robotic systems in a natural and convenient way. The ability of each user interface to be applied to a multiple-user feeding device will be discussed separately.

The following section introduces different user interfaces that have been used so far in rehabilitation devices and systems and that have the potential to be applied to feeding machines.

2.6.1 User Interfaces for Rehabilitation or Assistive Devices

The usefulness of robotic devices is largely dependent on the degree of independence which they provide to their operators [48]. Shortcomings in the user interface can act as major restrictions to the widespread use of the robotic systems in human service [49]. Human factors guidelines [50] for user interface design suggest to design it: 1) for ease of use, 2) to enhance user productivity, 3) to reduce stress on the user, and, 4) for ease of learning. The following sections introduce and summarize features and drawbacks of different possible and available user interfaces for interaction of the user with a robot or a machine.

Button or Switch: A button is an easy to use input device which is able to enter just a single command. It needs both a pushing force and a pushing device (finger, or simple stick attached to the head/chin). For use with the elderly, buttons should be big, with big printed labels, and should require as little activation force as possible, especially for users with weak muscles.

A switch is also a simple and reliable input device which is able to be in the state of on or off to provide a single command, and can be issued by almost any body part, such as a hand, head, chin, or shoulder.

Blow-Activated Switch: Blowing into a tube may be used as an option for clicking a mouse. As its name suggests, it uses the power of blown air from the mouth instead of fingers; and the pressure of the air may be transferred via a tube [39-43]. It may be suitable for users with severe upper-arm disabilities who do not have breathing problems.

Bite-Activated Switch: Biting on a pressure sensor may also be used as an option to replace manually clicking a mouse. It may be suitable for users with severe disabilities of the upper-extremities, whose jaw muscles are functional and who can close their mouth and generate varying degrees of bite pressure. This interface has been used in Chameleon [53], which is a body-powered rehabilitation robot.

Foot-Activated Pedal: Typically used in seated positions, a foot activated pedal is a simple interface which uses the force of the foot to move a robot arm. Foot movement information may be transferred to the robot arm by way of cables. This is an appropriate device for those who have enough ability in and control of their legs and feet, and want to have control on the robotic arm by themselves.

Joystick: A joystick is an input device for controlling forward, backward, upward and downward movements. It provides an easier grasp than a standard mouse for those who have grasping problems. Some assistive devices such as wheelchair-mounted robots, Manus [52] and My Spoon [23], are equipped with this device as an optional interface. However, people with cerebral palsy, stroke patients who omit stimuli from one side, and quadriplegics may be unable to make fine movement corrections necessary to use a standard joystick [51].

Touch Sensitive Panel: A touch sensitive panel is another button-free input device. It has a single, solid-state sensor pad that can be activated by human touch. There is no membrane to tear, crack or degrade over time; no moving parts to wear and potentially fail; and no need of significant force. It is completely sealed within a rigid, laminated substrate that is impervious to many challenging environments.

Laser Pointing Device: A laser pointing device is another input tool which may be used for those who cannot use their arms properly. It can be attached to any part of the user's body (such as the head) to point to a control panel of a monitor located at a distant location. This interface has already been applied in a feeding device [43-45].

Biosignals: An electrocardiogram (ECG or EKG) records the electrical voltage in the heart in the form of a continuous strip graph for screening and diagnosis of cardiovascular diseases. Electroencephalography (EEG) is the neurophysiological measurement of the electrical activity of the brain. They are very sensitive to noise and are non-stationary (time varying with interacting external environment). Electromyography (EMG) is the recording of the extracellular electric field potentials produced by muscle. These biosignals can be used as input when cameras or microphones are not desirable [54] and a more natural way of communication is preferred; however, they involve very complex time sequential data.

Vision System: A vision system is one of the most popular interfaces used for intelligent devices. It typically has three parts: a camera, frame grabber and image processing unit. A camera captures the image and sends out a stream of video data, and then a frame grabber receives this stream and stores it in memory as an array of digital pixels. A processing unit identifies features of interest in a digital image. It usually provides information regarding a subject or object. In the case of a feeding system, it can be used for detection of the user's mouth and recognition of food, utensils, plates, bowls, or cups depending on the application. Vision systems have already been applied for feeding devices such as ISAC [36-38], Robotic Food Feeder [39-41], and Assistive Robot Hand [44].

Voice/Speech Recognition: Voice or speech can be used to convey input commands in a natural and easy way for communication with a machine. Voice or speech recognition converts the natural linguistic commands into computer instructions by passing through three steps: feature extraction, measurement of similarity, and decision making. However, when the user's voice is not very clear or the environment is noisy, the recognition and information extraction might be error prone and difficult to use. For the case of a feeding device, the use of voice recognition was not recommended for My spoon [23] since the mouth was usually full while eating; however, it is used in ISAC [36-38] and Assistive Robot Hand [44] for getting the commands from the users or confirming them.

Body/Hand Gesture: A body gesture is a natural, vision-based communication method that provides many options for users to interact with a machine as long as the interpretations of gestures are defined for the machine. The beauty of this interface comes from the fact that movement can be interpreted as a meaningful gesture with no explicit indications of the beginning and end of the gesture. However, some problems arise when there are inconsistencies between different users attempting the same gestures and also across different trials where the same gesture is attempted by the same person. Persons who intend to use gesture interfaces must have the ability to lift their hand or body part within the image frame. They should also be cognitively aware of the meaning of each gesture and be able to learn and remember them.

Eye Blink: An eye blink sensor can be placed near the user's eye to trigger a mouse click using blinking, and to enable communication using blink patterns. The device automatically detects a user's blink and accurately measures its duration. Voluntary long blinks trigger mouse clicks while involuntary short blinks are ignored, and sequences of long and short blinks may be interpreted as semiotic (any material thing that signifies) messages. There is no need for manual initialization, special lighting, or prior face detection. People who do not have the ability to use their hands, head, shoulder, chin or other body part to active a switch or button, or cannot hold their neck and head up in order to operate a machine may benefit from the eye blink sensor.

Facial/Emotional Expression: Facial or emotional expression-like gestures [55] are very natural communication methods that may be used to interact with machines. Each facial expression such as sad, happy, surprised, would be understood differently and would send a specific command to the machine. Some of the challenges in interpretation of the expressions are: complexity, ambiguity, and subjectivity. This interface may be suitable for people with speech and hearing impairments.

Head/Eye Movement: Eye or head movement may be used by a person interacting with a machine as a control signal. Eye or head movements are detected by image processing; however, detecting the movement may be different with poor lighting conditions [56].

Eye Gaze: Eye gaze [57], which can act as a pointer and command sender, is a biological signal related to eye movements that indicate a person's interest in their surrounding. Human intention is determined by estimating the eye gaze direction; however, eye drifting and blinking may cause problems. The information of face direction is necessary for gaze estimation. A user can move a computer cursor using only eye-gaze or instruct the robot to pick up objects by looking at them steadily.

Eye Mouse: An eye mouse, often called an "ocular prosthesis" [58], helps people with severe upper-limb disabilities to control a computer by estimating the eye gaze direction of the user, and to locate the mouse pointer of a computer at the fixation point of the user's gaze. A small camera or binocular eye-tracker, with the help of infrared sensors in front of the user, tracks and records the eye movements. The data would be processed by related software to convert these movements into mouse movements, mouse clicks or double-clicks. Systems that are equipped with a display or monitor and have a graphical user interface where the user is supposed to enter commands or choices on the screen may benefit from this user interface.

Light: Light can operate as a simple output signal in the role of a user interface. It might be used for warning, reminding, or getting attention, when a device emits light at a specific time. Handy 1 [34, 35] used light to scan different foods inside a tray. When it scans the user's desired food, the user indicates their choice by pushing the assigned button for that food section.

Graphical User Interface: A graphical user interface (GUI) uses the graphical images to represent information and actions that are available to users. A well-designed GUI makes it easier for users to interact with a machine. An effective GUI facilitates the direct manipulation of data, learning process, and interpretation of commands. It allows a user to select from among a dozen tasks and to select options within those tasks and it sometimes can be used as a reminder (if it is not complex) for those who have problems remembering commands. Some components of a GUI include a pointer, pointing device (e.g. mouse or trackball), icons (which represent commands), desktop (area for grouping icons), windows (for running different programs and displaying different files) and menus (to give choices). The only feeding device that has used a GUI for the user interface so far is Robotic Food Feeder [39-41].

Cathode-Ray Tube Display: A cathode-ray tube display acts as an output device that shows either the images taken by a camera or graphical pictures or commands. It is used to: indicate status, identify a function, instruct, give warnings, and display qualitative or quantitative information. If the environment is very noisy or if the information to be displayed is complex, a visual display might help for a more convenient communication with the machine.

In the case of a feeding device, a display has been used to show a picture of each food position to let the user select the desired food, or to show the partial or full picture of user's face, to allow them to direct the robot manipulator toward the mouth by choosing the mouth location on the display [39-41]. Although feasibility of this interface is presented in [39-41], nothing is mentioned regarding the time it takes for the user to get the next bite.

Auditory Display: Auditory display is an output device which is used when an immediate response from the listener is required, such as to an alarm, or to a reminder or for confirmation of a choice. Auditory displays may consist of simple tones, complex tones and spoken messages. Tones may be continuous, periodic or non-periodic. Complex tones consist of sounds having more than one frequency component. Auditory signals should be recognizable from the noise or other auditory signals. Therefore it is recommended to use signal frequencies that are different from those of the background noise to prevent masking. The spoken messages should be short and simple; if the message is complex it should be presented in such a way to get the user's attention first and then give the exact information in the message.

Auditory display, used as a spoken message, is applied in the Assistive Robot Hand [44] to be able to confirm the existence of the objects on a table with the user and to verify the user's choices. It provides an optional interface in case the image processing system fails. Auditory display can also be used to remind a user of the necessary steps of eating. This is useful for those having memory problems associated with Alzheimer's disease and Dementia.

The summary of the aforementioned user interfaces are shown in Figure 2-16.

2.6.2 Discussion of User Interfaces

Among the simple devices available as robot user interfaces, switches or buttons have the advantage of being very simple. For the elderly, who may have poor vision, buttons should be large in size, with large labels and they should be easily accessible. A touch sensitive panel, however, has the combined advantages of having no moving parts that might make it susceptible to malfunction, and it is completely sealed and impervious to food or drink spills which make it a good candidate for the feeding system. In addition, joysticks [50], which may be acceptable for users who have retained some motor dexterity in their hands, may not be suitable for people with upper-extremity disabilities, since they require some mechanical force to be used as a control device.

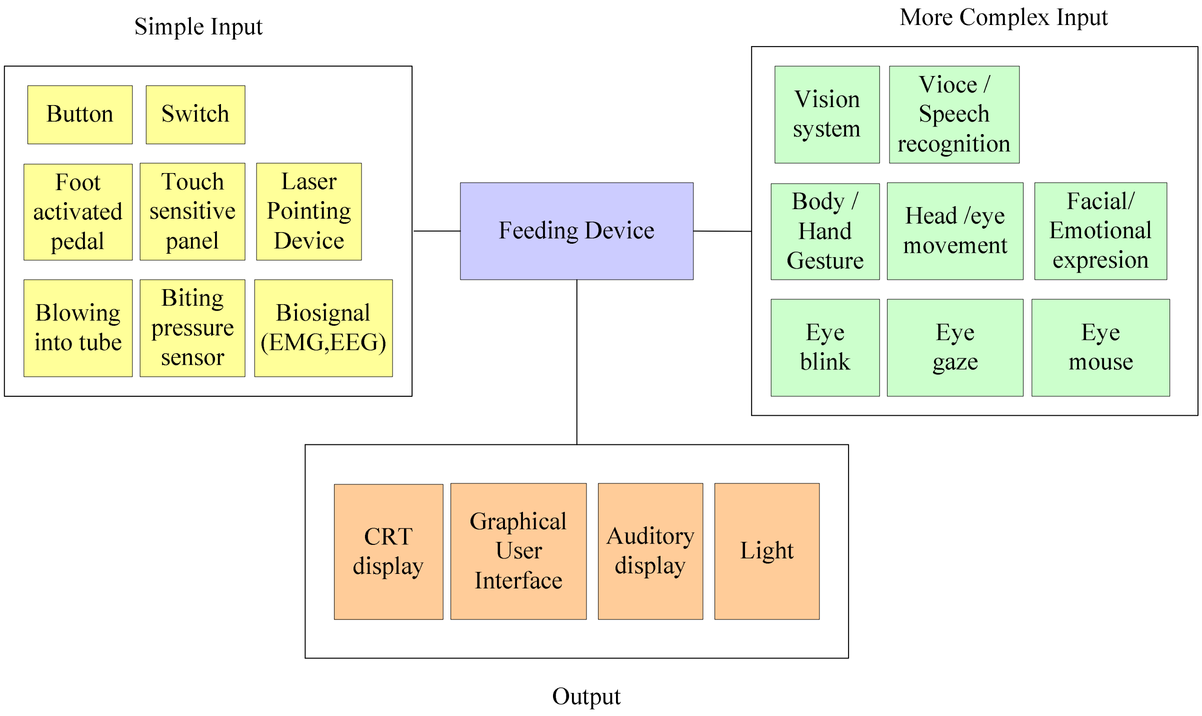


Figure 2-16: Categories of different user interfaces.

Table 2-4 specifies how much users of different interfaces are familiar with each device. In terms of choice of an input device, the majority of disabled people are only familiar with the joystick and remote control. That is, they will not hesitate to use such an input device [51].

Table 2-4: Input device familiarity [51].

Type of Input Device Used as Interface	**Familiarity of the Users**
Joystick	84%
Remote control	72%

Head movement sensor	Less than 5%
Roller-ball control	
Chin operated control	
Eye movement control	
Ultrasonic sensor	
Voice activated	
Sip & puff switches	
EEG based-switch	

Among the more intelligent methods of user interaction with robots, the vision system [36-41], [44] and voice/speech recognition [38, 44], have been utilized in systems that are specifically used for feeding of one disabled person. However, to date there is no record of applying the other user interfaces such as eye blink, human emotion/intention (bio-signs), hand or body gesture, head/eye movement, biosignals (EMG, EEG, ECG), facial/emotional expression and eye gaze for the purpose of feeding the disabled or assisting the elderly in an eating task.

Some earlier intelligent feeding systems benefited from having light, signal, sound, animation and graphical images to warn users about unreachable points/locations, or the approach of dangerous situations or areas, to scan a food tray (with light) [34, 35], to get confirmation of the receiving command (for speech synthesis) [44], and to command by a menu displayer (monitors, CRT displays and GUI) [39-41].

In general, some of the abovementioned interfaces may not be suitable for multiple-user feeding robots that are intended to be used in dining areas with more than 20-30 people. One of the primary intentions of the present study is to develop an assistive device to be utilized in dining areas of senior homes, which are typically furnished with several four-seat tables in a single room. This makes the environment noisy when residents are eating. Even if the volume is kept to a minimum, external sounds may still interfere with the user’s voice commands and, in turn, make it difficult for them to hear sound signals from the system.

Furthermore, for the proposed system, it may happen that two or more users issue commands at the same time and since they are sitting close to each other, differentiating their voices/commands will be a problem. Speakers can be applied for sound output only in restricted conditions. The sound can be transferred to each user by an earphone to prevent making additional noise and interfering with the other sounds from adjacent tables. In addition, if a visually-based interface were to be used instead, variable lighting conditions may make seeing and identifying objects difficult for the users. Also, the use of a laser head pointer may not be feasible for seniors with head tremors.

As discussed in the next chapter, many of the elderly may not be able to raise their hands properly or hold their fingers in specific configurations to communicate with the robot using gestures or other hand-related signalling. Indeed, not only do many seniors have problems in grasping and flexing their fingers, but to assign a gesture for a specific command and expect those gestures to be remembered, will likely be beyond the abilities of some elderly users. As training such a population would be a challenge for any interface, it was recommended to use a system that needs little to no training.

After reviewing different design ideas, analysis of the available products in the market and characteristics of end users, the elderly population was chosen as the target end user population of a new feeding device. Since many elderly live in senior homes, and none of the previous designs have been considered for use in such environments, the project focused on designing a feeding device which can meet many of the elderly user and caregiver requirements in the dining area of a nursing home. The next chapter will discuss the observations made of seniors and their caregivers during meal times at a senior home to better understand the needs of potential users of the proposed device.

Chapter 3

Observation

3.1 Observation Objectives

Despite previous research efforts related to task analysis and user demographics [11] of rehabilitation robots, none have investigated eating behaviour of elderly people in the dining areas of senior homes in order to solve the problem of feeding difficulty. In an effort to better understand the mealtime needs of elderly users in senior homes, observations were made of residents at the Village of Winston Park, a senior nursing home, in Kitchener, ON, Canada. There are approximately 95 residents, mostly 65 years of age and over, in regular and special care units there.

The main objectives of conducting the observations in the nursing home were to more closely investigate the eating tasks or procedures of elderly or disabled people in order to: *a)* find the potential users of the feeding machine; *b)* estimate frequency of their needs for such a system; *c)* understand the user's characteristics, behaviour and physical or mental capabilities; *d)* investigate the problems that hinder the potential users' ability to eat or that make eating very messy and/or lengthy; *e)* determine the design constraints; *f)* explore the features that should be added to or removed from the system according to the user's impairments; *g)* inspect different types of foods served, special utensils used and the methods applied to handle each kind of food while eating; and *h)* determine the feasibility of different human-machine user interfaces.

The physical and cognitive differences that may exist among users are important in the design of a feeding system. These are therefore discussed in the next section.

3.2 User Differences and Related Data

Each user has a unique combination of skills and limitations that contribute to their behaviour. User differences that must be considered during the design include: 1) anthropometric and biomechanical differences, such as body dimensions, static and dynamic strength, and motor skills; 2) differences in perceptual capability, such as short term and long term memory, spatial and sequential processing skills, and learning; 3) differences in affective attributes, such as level of anxiety, tolerance for frustration, and the need for status or recognition [86]. In general, the robot should be designed so that it can be safely and effectively operated by users with varying capabilities.

The basic steps for the correct use of anthropometric data are to: 1) define the anticipated user population; 2) select the percentage of users that is to be accommodated; 3) identify all body dimensions that are relevant for the design of the product; and 4) obtain an appropriate anthropometric data table and find the values that are needed. The observations made at the senior home helped to complete the first two steps by providing useful information about the user population. The related tables (anthropometric data) for the last two steps are provided in Appendix A. Relevant anthropometric dimensions, specifically for the feeding system, are: sitting height, sitting mouth height, sitting eye height, arm reach, head reach, and rotation angle of head.

The appropriateness of anthropometric data depends on the similarity between the sample used in the survey and the population of anticipated product users. Designing for persons confined to wheelchairs and the elderly presents special challenges. The eye level and functional reach envelope for a person in a wheelchair are significantly different from those of an ambulatory non-disabled person. Since body dimensions vary with age, it is important to know the ages of the product users. In addition, body dimensions may vary from generation to generation.

The next section reflects the questions raised before and during the observation sessions, followed by the answers to those questions and a discussion of the findings. The conducting of observations received ethics review and clearance from the Office of Research Ethics and was approved by the Human Research Ethics Committee at the University of Waterloo (UW ORE). Appendix B contains the authorization for this observation by the Office of Research Ethics.

3.3 Observation Results

Observations were conducted in the dining area of both sections of the nursing home: the regular care unit and special care unit. All residents, eating in dining area, in both units were observed in five separate sessions during mealtime over a two-week period. The elderly with cognitive problems, such as those with moderate to severe symptoms of dementia and Alzheimer’s disease, received particular attention in the special care unit. Some residents in this unit were physically healthy and did not have any difficulty handling tasks that needed muscular ability and coordination while eating. People who received care in the regular care unit predominantly demonstrated physical difficulties, although a few exhibited symptoms of the beginning stages of cognitive problems such as dementia. Table 3-1 summarizes the observation findings.

Table 3-1: Observation results of the nursing home of the "Village of Winston Park" senior home.

Observed Facts	**Findings**	
	Special Care (SC)Unit	**Regular Care (RC) Unit**
Number of residents	35 (36.84% of total)	60 (63.16% of total)
People who had Alzheimer's symptoms	All	None. Some of them were in the early to intermediate stages of dementia, but they were able to recognize the required eating process.
People who had upper limb physical disability that hindered the eating process (were unable to feed themselves)	2 were not able to use their hands to feed themselves. (5.7%)	24 (40% of RC) 40% of regular care unit population
People who had upper limb physical disability that made the eating process very difficult or very long and untidy (spilling food or drink)	Lack of strength in the hand to grab the utensil or the cup was observed in many cases. Hand tremor and lack of strength were the biggest cause of untidy eating process. Swallowing/chewing problems (identified by caregiver and type food) as well as lack of hand strength were reasons for the eating process being lengthy.	3-4 people used special utensils (spoon/fork with inclined head), because they couldn't grasp the required utensil properly in their hands. They often dropped the utensil because of lack of strength in their hands. Some didn't have enough strength to cut food by themselves.

Observed Facts	**Findings**	
	Special Care (SC)Unit	**Regular Care (RC)Unit**
People who had tremor in their hand while eating	Most of them had tremor in their hand, but its severity was different from person to person. A few people did not have this problem but they were slow in eating.	Most of them had tremor in their hand, but its severity was different from person to person.
People whose hand tremor hindered eating process	None. All were able to feed themselves, but it was untidy and almost half of the food in the spoon was gone before reaching the mouth.	
People who forgot the required steps in eating process (choosing food, choosing appropriate utensil, picking up food, bringing food to mouth, taking food off utensil, chewing, swallowing)	The forgetting of steps was not counted in detail. From one day to the other, various steps were forgotten. In one case the person didn't know what she should do. There were 18 people who could not choose the type of food.	None
People who could not cut their food	Those 12 who were totally dependent on nurses plus those who do not have enough strength in their hand to manipulate the knife easily and safely	Those 24 who were totally dependent on nurses plus those who do not have enough strength in their hand to manipulate the knife easily and safely
People who could not scoop up the spoon	At least those 12 who were totally dependent to nurses, but it differs from day to day, and from food to food	At least those 24 who were totally dependent to nurses, but it differs from day to day, and from food to food
People who ate meals that had already been cut	Maximum 25, sandwiches are not cut, the rest of them use pureed/gel foods	Maximum 36, sandwiches are not cut, the rest of them use pureed/gel foods

Observed Facts	**Findings**	
	Special Care (SC)Unit	**Regular Care (RC)Unit**
People who were physically able to feed themselves	23 (65.72% of SC)	36 (60% of RC)
People who were totally dependent on nurses or caregivers in eating	12 (34.28% of SC)	24 (40% of RC)
People who had problems in chewing or swallowing food	10 (28.57% of SC)	26 (43.33% of RC)
People who had to eat meals that were already pureed	7 (20% of SC)	19 (31.67% of RC)
People who could eat solid food	25 (71.43% of SC)	34 (56.67% of RC)
People who ate gel food or thickened fluid	3 (8.57% of SC)	7 (11.67% of RC)
The ability of the gel food to be sipped by a straw	It has not been tried yet in both units, but two nurses thought that it would be difficult to sip through a straw, because it is very viscous.	
People who used lipped and divided plates	There were 6 plates with some dividers. This helped users scoop up the food more easily. (mostly for independent people)	There were 7 plates with some dividers. This helped users scoop up the food more easily. (some were for dependent people)
Problems in sipping a drink with straw	Actually, this has not been tried yet to be able to find out the resident's personal preferences or their problems.	Problems in sipping a drink with straw

Observed Facts	**Findings**	
	Special Care (SC)Unit	**Regular Care (RC)Unit**
People who used small size spoons	Those who were fed by caregivers used small spoons	Those who were fed by caregivers used small spoons
People who would likely have the ability to choose the required steps if they are able to see a picture or hear a sound as the reminder	One of the nurses was thinking that it would be more confusing for these elderly if the numbers of choices are many, but it depends on what you show them or depends on their behaviour on a given day. He believed that this should be tested to determine its feasibility.	It's unpredictable, since their cognitive behaviour changes everyday. This was difficult for nurses to predict without a system to test.
The amount of each kind of drink presented for each diner	125 ml of juice/milk 250 ml of water 210 ml of coffee/tea	
People who were not opening their mouth when caregivers tried to feed them	All, some of them opened their mouth but the nurse had to push the spoon in their mouth and some part of food will remain on their lips.	2 persons are very difficult to feed. Most of the days, they close their mouth very hard even when the caregiver tries to push the spoon a little bit to their lip.
People who potentially can benefit from a feeding device	This cannot be found without testing any mock up; their reaction to such a device is completely unpredictable. It can be tested for those who have control of their head and neck and are able to open up their mouth.	One of the nurses believed that an automated feeder wouldn't work for those 24 people who are now fed by the caregivers, if they are supposed to reach to the spoon by themselves. Even if the spoon comes very close to their mouth. They do not have control or enough strength in their neck and head.

Observed Facts	Findings	
	Special Care (SC)Unit	**Regular Care (RC)Unit**
Sequence and pace of eating from one spoon to the other	Between 10-15 seconds for those who have swallowing or chewing problem, Between 5-15 seconds for independent people. Most of the time for independent people is consumed by scooping and lifting the spoon rather than chewing, swallowing, or struggling to move the spoon as smooth as possible to their mouth	Some were fast in chewing or swallowing if they were fed by somebody, but for some of them it took longer. It took almost 10 seconds for a person who was fed by a nurse and was not very fast in chewing and swallowing. (The sequence of eating from each spoon can be found for each person in next observations and the average time can be calculated)

Another part of the observation was exploring different typical foods served in the nursing home for each mealtime during a one-week period in order to categorize them based on their shape (e.g. solid, semi-solid, liquid, etc.), the way the diners handle them for eating (using hand, fork, spoon or knife), and the possible method a robot would choose to pick up that particular kind of food. This information is given in **Error! Reference source not found.**. This particular part of the observation not only specified the pick up method for the robot, but also revealed the frequency of using the spoon, fork, hand or both, which helped in deciding whether a fork should be used in the system at all. Table 3-3, provides the frequency of using each of the utensils.

Table 3-2: Different categories of different samples of food, desserts or salads.

Meals /Soups /Sandwiches /Desserts /Salads					
Food name	**Shape**	**User's utensil**	**Robot's utensil**	**Scooping with spoon**	**Picking up with fork**
Split pea & ham or soup/yogurt	Thick, blended	Spoon	Spoon	Possible, easy	Not possible
Carrot &thyme soup/fruit yogurt/ Cream of wheat/oatmeal	Thick, not blended, has solid material inside	Spoon	Spoon	Possible, easy, solid parts should fit in the spoon	Only for the solid parts
Tomato soup	Semi-thick; may have juice	Spoon	Spoon	Possible, easy	Not possible
Grilled cheese	Solid, semi-soft	Fork or spoon	Fork	Possible, if cut in small pieces that fit in a spoon	Possible, easy if the pieces not too small
Hamburger or Fish sticks/tartar	Solid, hard	Knife and fork	Fork	Possible, if cut in very small pieces	Possible, easy if the pieces not too small
Macaroni & Cheese	Solid with small parts	Fork or spoon	Fork/ spoon	Possible, better when macaronis small	Possible, better when macaronis big
Mashed potato	Solid, soft, sticky	Spoon/ fork	Spoon/ fork	Possible, easy	Possible, easy

Meals /Soups /Sandwiches /Desserts /Salads					
Food name	**Shape**	**User's utensil**	**Robot's utensil**	**Scooping with spoon**	**Picking up with fork**
Steamed Peas/beans/corn	Solid, semi-soft, has small parts	Spoon/ fork	Spoon	Possible, easy, if there are many left in the plate	Possible, difficult, if there are not many left in the plate
Beef/ Hot chicken /Hot dog sandwich	Solid	Hand or fork	Gripper /fork	Not possible	Possible, if cut in pieces that can be picked up
Toast/ Beard	Solid, fluffy or dense (depend on its type)	Hand/ knife	Gripper/ fork	Not possible	Possible, easy when cut in pieces and it is dense but difficult when it's so fluffy
Leafy salads (Lettuce, cabbage, spinach and mixed)	Solid	Fork	Fork	Possible, if minced	Possible, difficult when little amount of food is left in the plate or cut in small pieces
Mixed vegetable salads (cucumber, tomato, broccoli…)	Solid, semi-soft, minced, has juice	Spoon	Spoon	Possible, usual, when the pieces are very small	Possible, if the pieces are big enough to handle with fork
Jell-Os'	Semi-solid if cold	Spoon /fork	Spoon	Possible, usual	Possible, usual

Meals /Soups /Sandwiches /Desserts /Salads					
Food name	**Shape**	**User's utensil**	**Robot's utensil**	**Scooping with spoon**	**Picking up with fork**
Assorted cakes	Solid, fluffy	Hand/fork	Fork/ spoon	Possible if cut in small pieces, or wants to pick up small parts remaining in the plate, but not usual	Possible, if the pieces are not too small or fluffy to take apart when picking up
Pudding	Semi-solid	Spoon	Spoon	Possible, usual	Little possibility

Table 3-3: Percentage of usage of spoon, fork or both in a one week menu.

Utensil used for eating	**Percentage of usage in a one week menu**
Spoon only	42/139 = 30.21 %
Fork only	52/139 = 37.41%
Either spoon or fork	28/139 = 20.15%

3.4 Discussion of Results

3.4.1 Differences between Two Care Units

The observation sessions revealed that from the two separate available units in the nursing home, all residents in the special care unit were suffering from Alzheimer's disease but not necessarily from upper-limb disabilities. Some of them looked at the food on their plate but could not logically connect hunger to food or to feeding. They forgot the required steps for feeding themselves, even chewing or swallowing. Some of them were frequently in need of being reminded about the next task after finishing each step. According to the observations and also the nurses' experience, they behaved differently from day to day, with no regular or predictable pattern, and they easily got confused when they had many options to choose from.

The behaviour of elderly residents with cognitive problems, in response to a new device and the level of their adaptability might be quite unpredictable. Therefore, it may not be necessary to have a particular design of a feeding device for this population. However, the ways the machine and user interact with one another may be extremely important in ensuring a user's cognitive disabilities are addressed, to ultimately permit a comfortable and stress-free feeding. This suggests that, much focus of the design of a feeding system for this group of potential users may be more on the application of appropriate user interfaces. An appropriate interface would help the users obtain a good understanding of the environment and the required tasks for the procedures of eating.

Any device or method applied or integrated with a feeding system that can keep track of the forgotten, wrong steps and can guide the user through the next required step by reminding them and giving them the required instruction, would be extremely helpful. For this population, a feeding device equipped with an appropriate user interface(s) might assist those who suffer from upper-limb physical disabilities or malfunctions in addition to memory problems.

3.4.2 Elderly Problems and Behaviour in Regular Care Unit

Contrary to the special care unit, only a few of the residents in the regular care unit, were in the early stages of dementia and exhibiting short term memory problems. However, many of them suffered from upper-limb dysfunctions, which made it difficult for them to eat by themselves. In addition, having no control of their heads and necks, having severe head tremor, not being able to open their mouths to be fed, and severe swallowing and chewing problems, were among the typical physical difficulties that caused 40% of the regular care population to be completely dependent on caregivers to be fed. This suggests that if the feeding robot were to be programmed in such a way that it stops the utensil at a specific distance from the user's mouth, and thus not going inside the mouth (for safety reasons), those with the abovementioned difficulties would be unable to benefit from the feeding machine. They would be unable to reach the end of a spoon or fork and would need to be closely monitored by their caregivers to avoid unpredictable accidents.

Among the rest of the 60%, more than 40% had problems such as hand tremor, lack of strength in holding the utensil, and severe joint pain in arm, wrist, or finger. They had difficulties in manipulating the spoon or fork and directing it toward the mouth. In many cases, almost half of the food fell from the spoon because the person could not hold the spoon at a right angle after scooping. About 11.7% of the elderly used a lipped plate with dividers to help them more efficiently scoop their food. For each user, 3- 4 different kinds of food and desserts and 2- 4 cups were considered. Most of the solid foods (between 40%-60%) were already cut into pieces for those who did not have enough strength to do this task, and many of the foods (about 31.7%) were pureed for those who had chewing or digestion problems. Approximately 11.7% of the residents consumed gel foods because of chewing and swallowing difficulties.

The eating process was considered fast if the sequence of putting the spoon/fork into the mouth was between 4- 6 s and was slow if it was more than 10 s. The results showed that more than 43% of the people who had chewing or swallowing problems were slow or very slow in eating, while the interval between inserting the spoon/fork into the mouths of the rest of the individuals, who did not share those physical disabilities, varied from 5 to 15 s in the slowest cases. According to the observations and the caregivers' opinion, at the present time, there are many elderly people who can benefit from being assisted by such a feeding device in that environment, although there is some uncertainty in the level of their adaptability to be expected should they attempt to utilize such a system.

In both the special and regular care units of the nursing home, many elderly people dined together at standard four-seat tables. The limited time allocated for each meal and the daily progression of physical and mental disabilities of the elderly made mealtime very challenging not only for the residents, but also for their caregivers. Indeed, one nurse could respond to a maximum of two diners at the same time and could only manage to respond to the needs of all diners with the assistance of the limited number of staff members available.

3.4.3 Multiple-User System

The idea of having a machine that is capable of simultaneously feeding multiple users in such places as nursing homes seemed advantageous for many reasons:

1) Assignment of one feeding device to a maximum of four people in such institutions would dramatically reduce the number and consequent costs of machines and nurses or caregivers.

2) The time-gap required for one person to chew and swallow could be allotted to feed another person sitting at the same table; particularly since the gap might be longer for elderly individuals with slower paces of eating.

3) To date, almost all of the proposed feeding systems to assist elderly or disabled people with upper limb dysfunction, have been applied to single-user use. Little effort to design a multiple-user feeder machine has been made. The novelty of a multiple-user feeding system would be additional motivation to test the feasibility of the system in environments where it would be useful.

The next chapter provides details of the design of a multiple-user feeding robot, food tray and the setting of the whole system, along with both the user and the robot characteristics.

Chapter 4

Design of Feeding Robot

The focus of the design is a system capable of feeding multiple elderly or upper-limb disabled adults using a serial articulated robot located on a table with a maximum of four seats. The typical characteristics of the potential users, robot, and the design assumptions needed to be defined before proceeding to the design. Throughout the project, a virtual feeding robot system has been used to evaluate the feasibility of the proposed device as a multiple-user feeding system. The design of a virtual prototype consisting of a robotic manipulator, food trays, and table are explained in this chapter and the feeding process is planned for multiple users. The virtual prototype not only provides us with the information needed for fabrication, but is also used as a communication tool, for architectural development and evaluation.

4.1 User Characteristics

The user characteristics are based on the observations made at the senior nursing home. However, for this part of the project, some limitations on elderly motion and behaviour will be applied to the system. For example, the ability to keep the neck and head upright is applied for safety reasons, to prevent choking while eating.

Table 4-1: Feeding robot user characteristics.

Profile	User Characteristics of Feeding Device
Age	Varies (adults – elderly adults) (No children at the present time)
Gender	Female and male
Vision status	Able to see and read labels, buttons or switches

Profile	User Characteristics of Feeding Device
Mental status	Cognitively aware of the environment (Those with sever dementia and Alzheimer's symptoms are not included as target users)
Physical status	Those who have weak muscles or joints in their hands or arms, or suffer from muscle stiffness and cannot grab or handle a spoon or fork easily, or have significant tremor in their hands while eating, are the target users of this product. The user has the control on neck and head muscles.
Hearing status	Able to hear all sounds, words, tones, or characters
Talking status	Able to articulate clearly, such that all words and characters are recognizable by others.
Level of motivation	Gaining independence in eating may be a great motivation for elderly or disabled people who want to eat neatly and speedily with little to no effort, but are currently in need of other people's help to do so.
Occupation	Usually are unemployed, retired, and jobless and reside in senior houses, nursing homes or hospitals where they receive special care.
Specialized skills	It should be easy to use but for long term care, training would be provided
Previous experiences with similar products	It is possible that none of them have experience being fed by a machine/robot. Training may be necessary just to introduce the features of the machine and how or when to use them.

4.2 User’s Safety

User safety is a very important factor to be considered in a feeding system since the robot and its users will be closely interacting in the same unstructured environment. In an unstructured space, there are some possibilities for user injury; for example, if the robot accidentally pushes, pinches, or hits a user’s body part. Some criteria should be met to guarantee user safety. These factors are as follows:

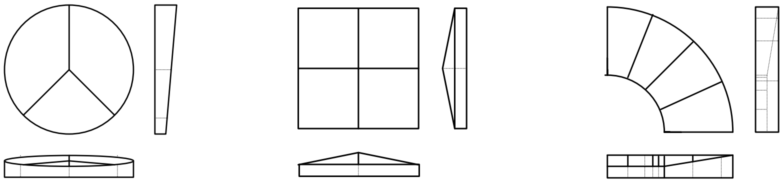
1. The robot’s end effector should avoid hurting the user by stopping at the closest defined distance to the user’s mouth. This will be more important when the robot is using a fork which has pointed tines. If the location of the user’s mouth is beyond the workspace of the robot (when the user is farther than the defined allowable distance from the robot), the robot should notify the user to sit closer to the table’s edge. To reduce the need for such notification, information related to the proper sitting distance from the table can be given to the user during the period of training for the new feeding machine.
2. The user must have sufficient control of their neck and head, enough to keep it in an upright position or at an angle that would be safe in the nurse’s opinion. This decreases the potential of choking while swallowing. The end effector should not reach the user’s mouth, but should force the user to reach slightly for the spoon. The amount of force applied by the robot should stay within a range where the likelihood of injury to the user is minimal. Also, the spoon or fork should not retract when it is inside and touching the user’s mouth.
3. The robot should not work when the user has a continuous head tremor. Not only would the condition make the user’s mouth very difficult to track, but it may cause the force sensor at the end of the end effector to be unreliable when touching the user’s mouth. Incorrect data may lead to an extra applied force to the user that causes injury.

4.3 Assumptions for Using the System

It is assumed that some issues related to food, the user and the environment will be taken care of or checked by the care or service providers in the dining area. For example, large pieces of solid foods that would typically require a knife and fork would already be cut into bite-sized pieces before the user begins their meal. Sandwiches and other solid foods that only require a fork, once cut into pieces, would be placed into the shallowest section of the food tray. Soups or liquid foods would be poured into the deepest section of the food tray; and solid/semi-solid foods which require a spoon to be scooped, would be placed in the remaining sections of the food tray that have medium depth. Also, the contents of drinking cups (juice, milk, water or coffee/tea) would already be known to the user either by labelling, color or by their fixed position. The user, who would have control of his/her neck and head, would be seated in an upright position or an angle that is safe for eating.

4.4 Robotic System and Food Tray

According to the results of the observations, a food tray has been designed that could hold four food sections in addition to four cups, and one spoon and fork for each user, as shown in Figure 4-1. In this section, the importance of food tray design (the arrangement of food sections, cups and utensils) in responding to the user's needs and simplifying the robot's function in the whole system setup is discussed.



(a) (b) (c)

Figure 4-1: Some possible shapes for the food tray (a) circular plate (b) square plate (c) arc plate.

From some of the possible shapes, the arc-shaped plate shown in Figure 4-1(c) has been chosen for these reasons: 1) The robot can be located in the center of the arc ,which makes it easier for the robot to feed multiple persons; 2) Scooping the food will be much easier compared to the square or round plate with three or four compartments, as shown in Figure 4-1(a) and Figure 4-1 (b); and, 3) The food trays can be put beside each other with one robot at the center for feeding four users (as shown in Figure 4-7)

4.5 Cups, Spoon, and Fork

Regular cups with more than 250 ml capacity have the following dimensions: a mug is 80 mm×95 mm (height) and a normal glass is 50-70 mm×120 mm (height). The height of the container depends on the cross sectional area of the container, but the volume should be at least 250 ml. For this design, a circular cross section has been chosen. Drink containers should have handles to make grasping easier for the robot gripper; and the shape of the handle should be carefully considered since it will affect the type of gripper, grasp type and grasp pose of the end effector.

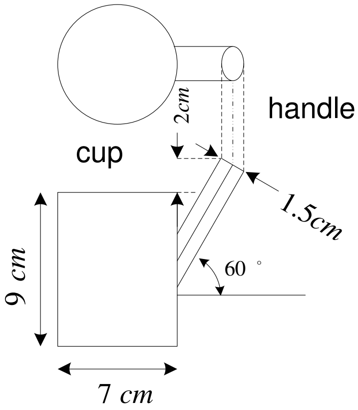


Figure 4-2: Dimensions of the cup and its handle.

To simplify grabbing the handles of the cups, forks and spoons, all the handles are cylindrical with the same diameter, at the same angle, 60 deg, with respect to the horizontal axis, as shown in Figure 4-2. Since the robot is placed at the center of the table, there will not be any difference in the robot's ability to reach each user. It is planned to simplify the robot's task by assuming that the robot places the cups, forks and spoons in the same position and orientation in each user's tray. The spoons or forks have holders to keep them in a predefined position and orientation. The dimensions of typical spoons for adults are given in Table 4-2.

Table 4-2: Dimensions of a typical spoon for adults.

Spoon	Handle length	Total length	Base width	Base length
Size	120 mm	180 mm	40-43 mm	60 mm

The size of the food plate, the number of sections and the positions of the cups should be specified in the food tray layout. The capacity of each food section is based on the capacity needed for a typical serving; and the numbers of food sections depends on the number of different foods that are served for each individual. The inner shape of the food compartments should be specified based on the type and shape of the food. Liquid or semi-liquid foods, such as soups, need a deeper plate with an inner structure ergonomically designed to facilitate the scooping process. Solid foods, which are typically cut into pieces and are assumed to be picked up by a fork, can be placed in shallow plates without specially modified inner structures.

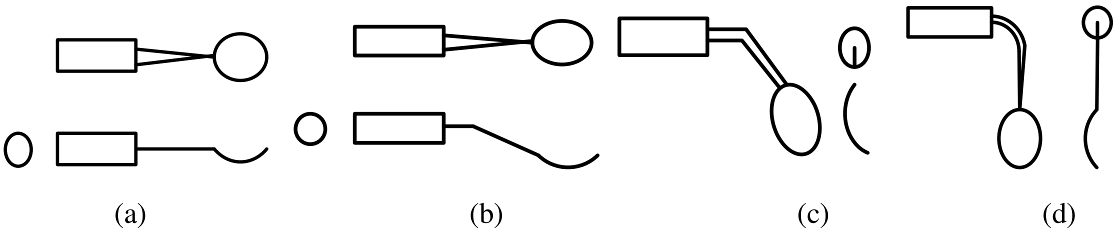
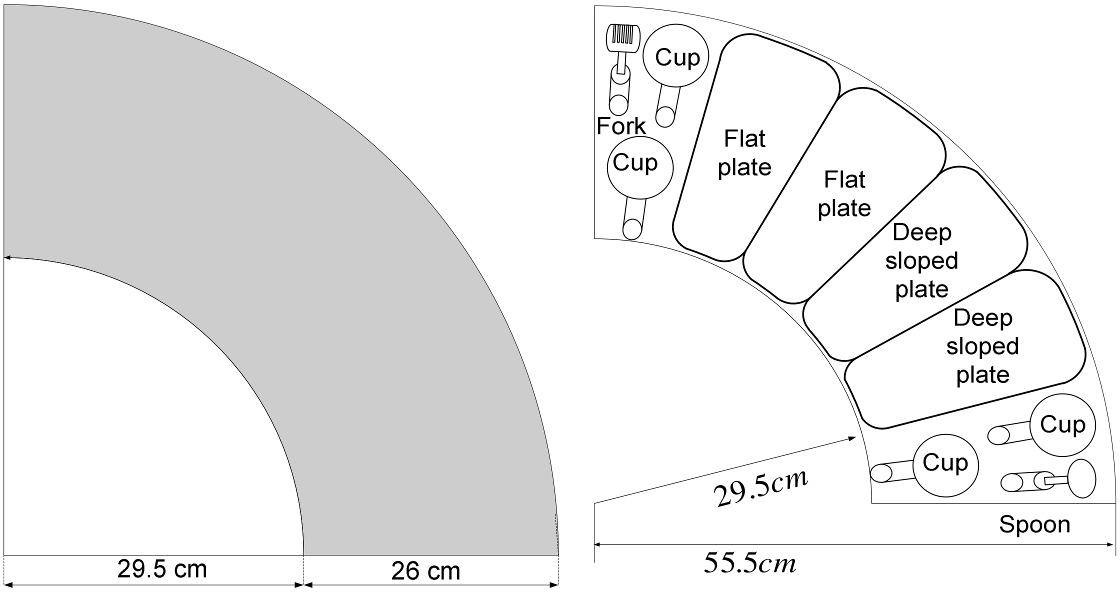


Figure 4-3: Possible feeding angles (a) straight spoon with thick handle for front feeding, (b) inclined spoon for easier scoop, (c) inclined spoon for semi-side feeding, (d) inclined spoon for side feeding.

The goal is to fit four cups and four food sections in the following available space: a 90° arc with 26 cm width and outer radius of 55.5 cm. Based on calculations of the minimum amount of food and liquid required by users, the positions of food sections, cups, spoon and fork, were determined in order to fit all utensils and food sections in the limited arc-shaped area in Figure 4-4(a). The final layout of the food tray was set as shown in Figure 4-4(b). The area of each food section in this layout is approximately $275\,cm^2$, which is slightly more than the typical volume of each serving and it guarantees having enough space for food.

Two sections of the food tray are flat for the foods that are supposed to be picked up by the fork, and two sections of the food tray are deep and sloped for foods that are to be scooped up by the spoon. The amount of empty space is minimized and the available room is used for fitting four food sections, four similar cups, one spoon, and one fork. The food sections are located in the center of the arc and the cups and fork/spoon are positioned at the sides. The layout is considered almost symmetrical to make it easier for the robot to face each object in the tray with almost identical approach.



(a) (b)

Figure 4-4: (a) Top view of the considered area for fitting utensils, (b) Arrangement of the food plates, cups, fork and spoon. The directions of all handles are towards the center.

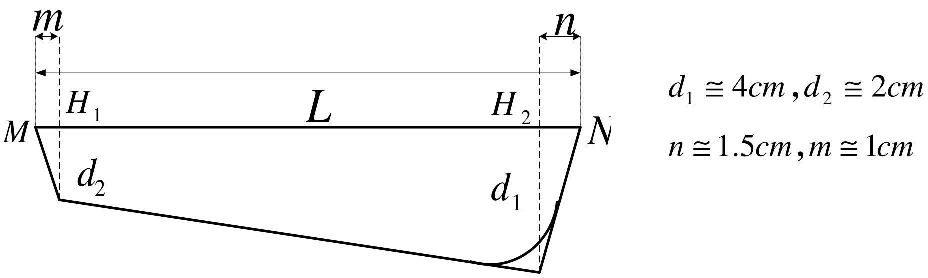


Figure 4-5: Deep sloped plate for liquid/semi-liquid foods/desserts which can be scooped by a spoon.

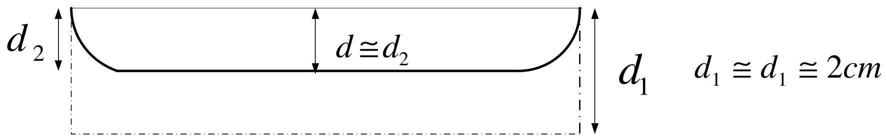


Figure 4-6: Flat plate for the foods/desserts which can be picked up by a fork.

After completion of each task, the robot arm can return to its last position, where the end effector and all arms are coplanar. If the waist turns slightly, it can align the arms in the plane for the object that is about to be placed or picked from the tray. As mentioned, the depth and inner shape of the food sections are specified according to the maximum required volume and the type of food. The design of the deep sloped plate, shown in Figure 4-5, has the following advantages: 1) The slopes on the sides of the walls match better with the slope of the spoon as it reaches towards the food and provides a smoother path as the spoon dips into and out of the food plate; 2) Rounding the sharp corner angles makes a better path or trajectory for the spoon; 3) The slope at the bottom of the tray helps the fluid or semi-fluid foods slide down and pool in the deeper points to ensure that any food remaining in the plate can be scooped by the spoon. However for foods that are supposed to be picked up by the fork, a flat shallow plate, shown in Figure 4-6, works better.

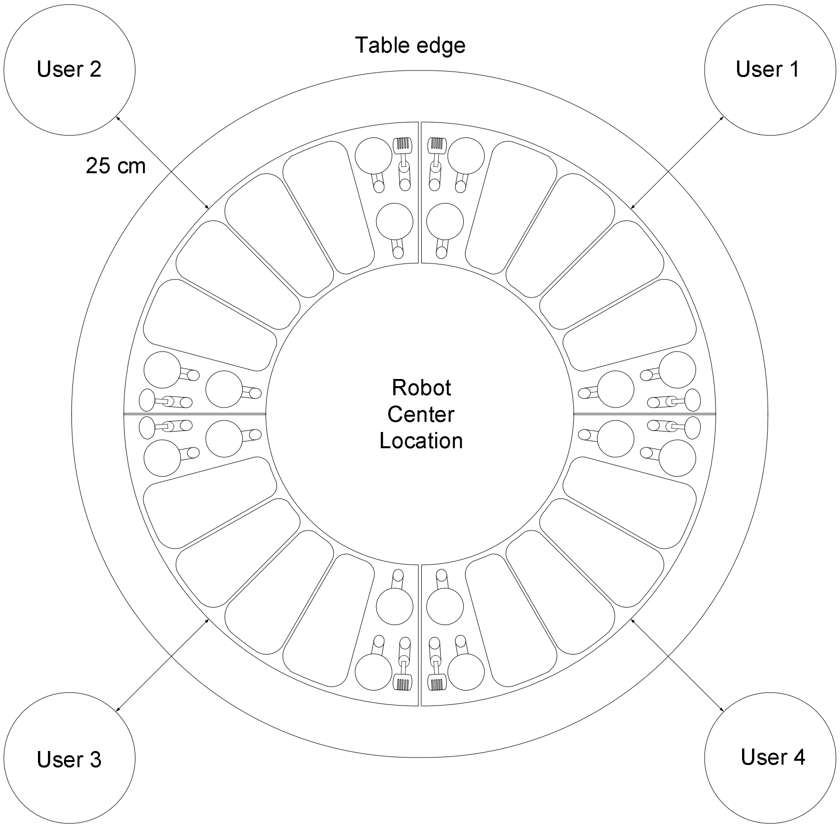


Figure 4-7: Top view of the position and arrangement of four food trays for four users, the users are at least 25 cm away from the food tray edge.

The position and arrangement of four food trays for four users are shown in Figure 4-7. Top view of this arrangement helps in the understanding the distance of the user's mouth from the edge of the table. The users in this design are at almost 15 cm away from the edge of the table and 25 cm away from the edge of the food tray. A three-dimensional virtual representation of four food trays containing deep and flat plates, along with four cups, a spoon and a fork, for each user, as well as, the robot in the center, were modeled in ADAMS, as shown in Figure 4-8.

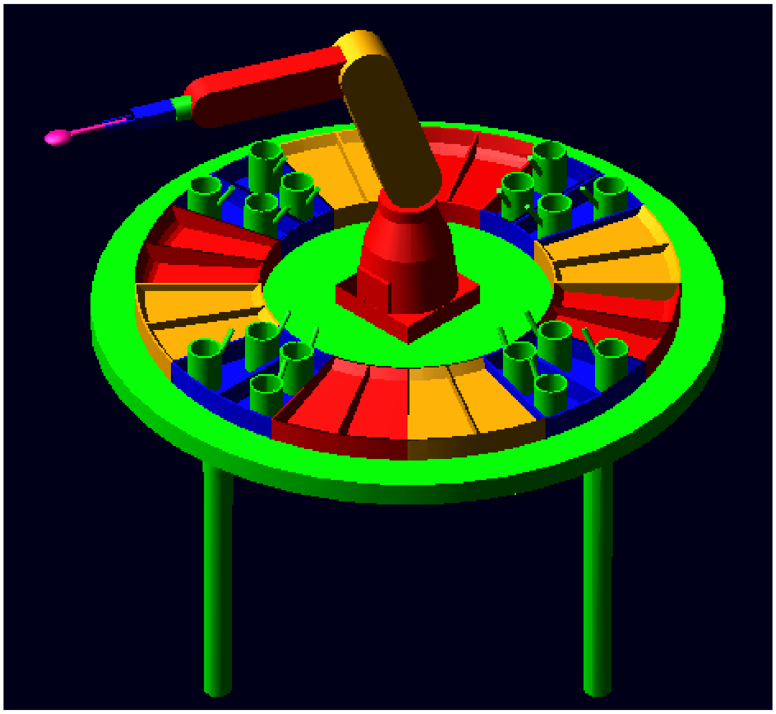


Figure 4-8: 3D model of the robot located in the center of the table along with four food trays.

4.6 Expected Characteristics of Robot

Before selecting, designing or finalizing the feeding robot, there are some expectations that were aimed to be met which are listed below:

1. It is small enough to fit on a four-seat table with standard height of 72-74 cm (in an area with a diameter of almost 60 cm with no object inside and no extra obstacles).

2. It is able to feed 3-4 people at the same time.
3. It is a serial manipulator that can rotate almost 350-360 degree at the base to provide large workspace and respond to all users.
4. The spoon or fork lifts no more than the weight of the food, and, therefore, a payload of 2-3 kg is sufficient.
5. It can reach to predefined locations on the dining table to pick up a spoon, a fork or any of the cups for each user.
6. Feeds users different kinds of solid or liquid foods; provided the solid ones have been already cut.
7. It picks up the user's desired food each time by using an input device or command.
8. Scoops up the user's chosen food with the spoon and takes it to the user's mouth.
9. Feeding pace may be changed by the user. The eating process would be repeated until the dish is empty. The speed of the robot would be changed accordingly.
10. Feeding pace is expected to be matched according to the user's eating pace.
11. Optimally has optional user interfaces for different capabilities of the elderly or disabled users.
12. The operation does not require specialized knowledge of the user related to the feeding machines.
13. Minimum/No amount of effort is put into performing eating task.
14. It accomplishes the tasks safely with minimal supervision on the part of care providers.
15. It takes the spoon or fork to a position close to the user's mouth, but not into the mouth. (the safest distance should be defined)
16. In the case of having any kind of button or switch, to command or to control the machine, the button or switch should be big enough to be pushed, moved or grabbed by the user.
17. All written notes, warnings, names or pictures should be printed in big fonts to be seen by the users. (since most of them have poor vision)

18. The rotation angles of joints and the length of link should be able to provide the maximum reach between 800- 836 mm.
19. The height of the robot's waist is preferably lower than the user's eye level when the user sits behind the table (this is psychologically better since it is not too obtrusive).
20. In case of accident or emergency, the robot should be able to stop immediately.

The next section provides information about the selected robot which has similar characteristics to the desired robot. The reachability of the robot and the robot's workspace will be evaluated versus location of the user, especially the location of the mouth, and eyes.

4.7 Selected Robot

A six-DOF non-redundant robot arm is believed to be a general purpose device, since it can freely position and orient an object in Cartesian workspace [59]. For the purpose of this project and in order for the required robot end-effector to reach any position inside the workspace in any orientation, the manipulator also needs six-DOF. However in search of such a robot and before selecting one, the minimum or desired system requirements such as type of robot joints, length of links, maximum weight, maximum payload, maximum and minimum reach, and workspace of the robot will be specified based on determined user's characteristics and also on the feeding environment. Some of the data that impact on this decision are: the desired model configuration, strength and dimensions of a standard four-seat table to hold the robot on top, the weight of the utensils plus food and cups filled with drinks, the distance between the outer edge of the food tray with the edge of the table, the anthropometric data of a typical adult in a seated position, such as the height of the mouth and eyes, and the distance of the head and mouth from the table.

Considering the above important information and the aforementioned expected and desired characteristics of the feeding robot, a Thermo CRS-A465 robot was selected for the application. It has a weight of 31 kg and maximum 2kg payload on the end effector. The waist of the robot can rotate from -175 to +175 degrees. The maximum reach of the robot is 711 mm without the end effector and 864 mm with a standard end effector (not considering the length of the spoon or fork). The three joint axes of the 3-DOF wrist intersect at one point. This has the advantage of providing the closed form solution for kinematic and dynamic analysis.

To be able to evaluate the reachability of the selected robot's end effector, the schematic side view of the robot links and their rotation angles, as well as a standard table and one food tray for a typical user was used, as shown in Figure 4-9.

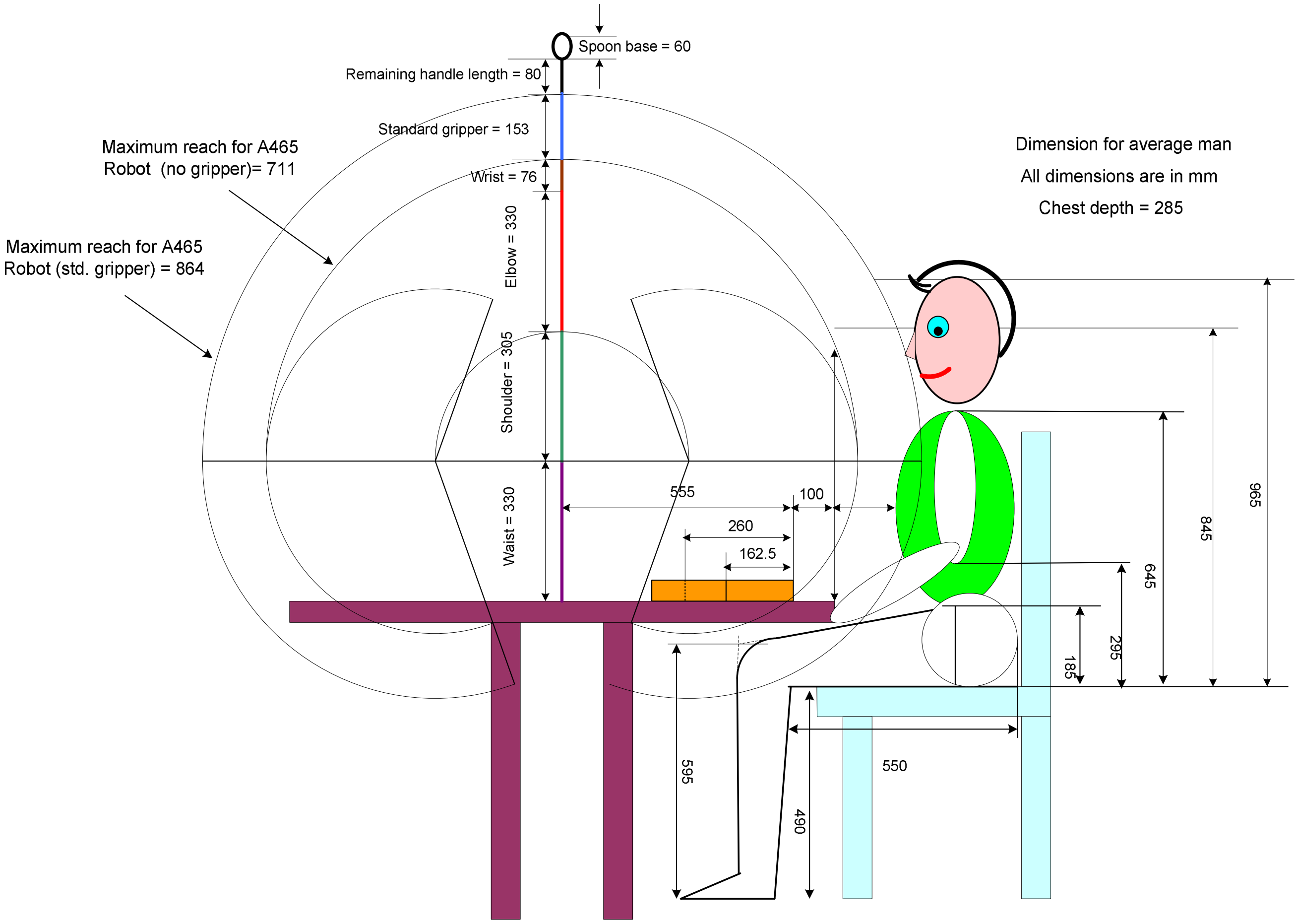


Figure 4-9: Average anthropometric dimension of an adult user [25], size of a typical standard chair and table, with respect to one food tray and also the proposed robot which has the dimensions of a Thermo CRS-A465 articulated robot (schematic diagram is to scale, dimensions in mm).

The anthropometric data (Appendix A) based on the maximum amount in the given range for the average size of an adult man, was used to represent the typical user of the robot. Most of the heights shown in Appendix A are slightly less for the elderly, 65 years of age and older, since their backs are more curved; and they shrink in size as they age.

To be conservative in workspace calculations, the highest body heights should be considered. This ensures that the robot's end effector should not have any problem handling the users should their mouths be located at a shorter height. As shown in Fig. 4-9, the selected robot is able to cover the desired points in the space and reach to the closest safe distance to the user's mouth. It is assumed that the user's mouth is almost 15 cm away from the edge of the table for safety reasons and the end of the spoon/fork is would not be further than the edge of the table.

The next step was to add cameras and specify their locations in the system for acquiring images from the users' faces and the food tray.

4.8 Adding Cameras to the System

To be able to both check the presence of users behind the table and track the locations of their mouths, four cameras are recommended to be used. In addition, to determine the locations of the central parts of solid food parts and check the presence of utensils or food parts inside the tray, four other cameras are proposed to be used.

Getting the images of the users' faces from the frontal locations and the food and utensils from the top locations would be better for this system, but since the robot is located in the center, the presence of cameras inside the borders of the food trays and finding a place for their installation would be a problem. The cameras, as shown in Figure 4-10 and Figure 4-11 are located beside the users, at the average height of the head and mouth.

The location of users' cameras are somewhere between the frontal and side view of the users. Tracking the users' mouths needs a separate algorithm to extract features of the users' faces, such as lip shapes and central locations. However for the sake of this project, the locations of the users' mouths are assumed to be in predefined positions, since facial feature extraction is not part of the project.

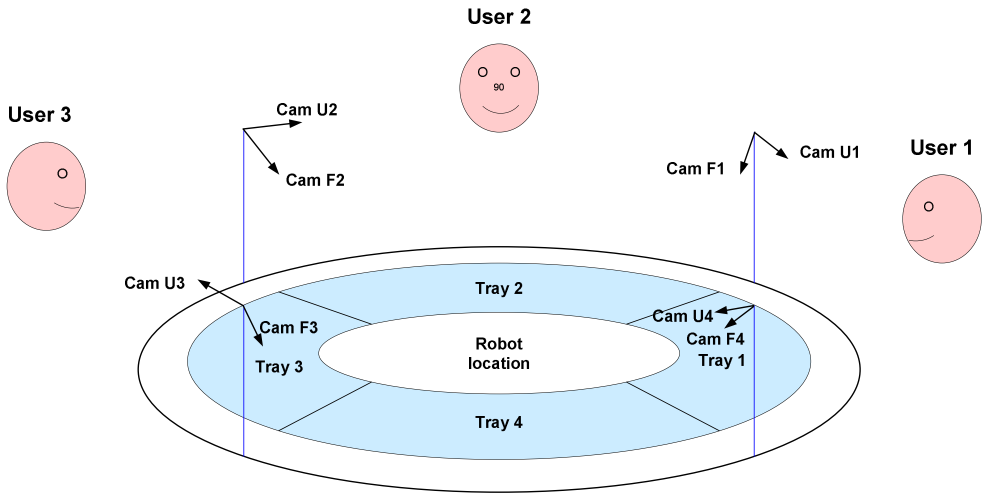


Figure 4-10: Arrangement of cameras versus food trays and users (user 4 is not shown). Cam U_i is tracking the i^{th} user's mouth and Cam F_i is recognizing food and presence of utensils in i^{th} tray.

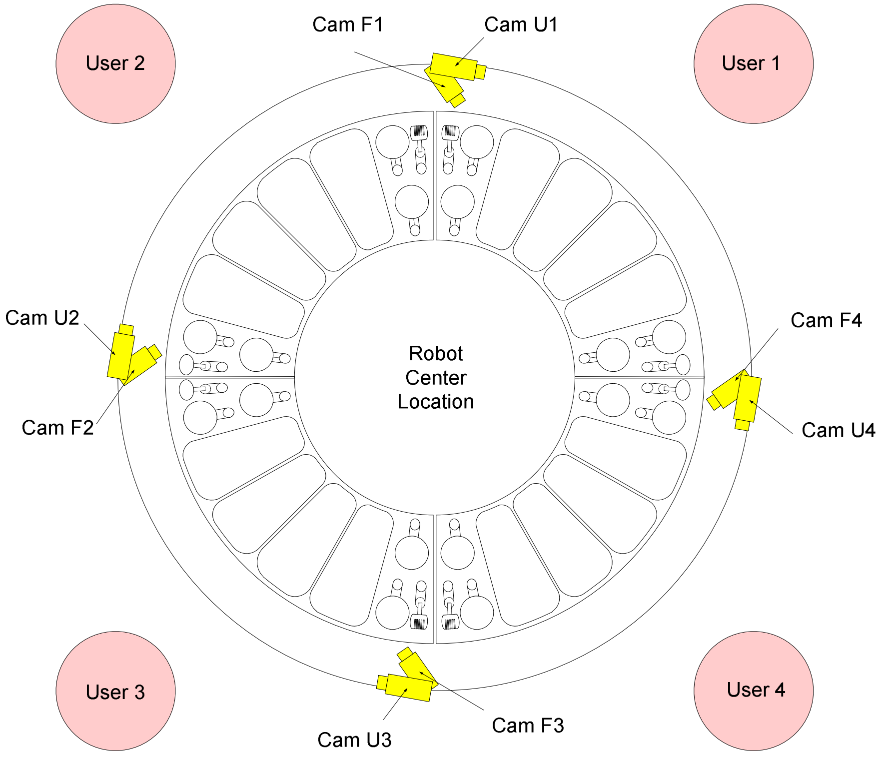


Figure 4-11: Arrangement of eight cameras with respect to the users and the food trays.

The locations of the user's mouth can be defined symbolically to provide the link to further research on the system. If the real-time mouth tracking is set up in the future, the result for the location of the lips can be substituted in the assumed locations.

The following section categorizes the required tasks which the robot should accomplish. A breakdown of each task into detailed subtasks was attempted.

4.9 Multiple-Users Feeding Procedures

The robotic and vision system are parameterized by defining the system variables. Table 4-3 lists all these variables and their reference names. Table 4-4 lists all the acceptable users' commands and Table 4-4 also lists the reference names of the functions and subsystems.

Table 4-3: System variables and reference names.

System Variables/Parameter	Reference name
Camera j j = 1:4 (for the face of user 1) j = 5:8 (for the objects on the table located on the side)	Camj
Image captured from camera j	imgj
User i (i=1:4)	Ui
Mouth of User i (i=1:4)	Mi
Food section k, user i (i =1:4)(k=1:4)	SECki
Fork, user i (i =1:4)	Fi
Spoon, user i (i =1:4)	Si
Cup m, user i (i=1:4), (m=1:4)	Cmi
Food section k, user i (i=1:4), (k=1:4) Food section 1,2 (for foods that should be scooped with spoon) Food section 3,4 (for foods that should be picked up with fork)	Ski
Length of the fork (same for all users)	LF
Length of the spoon (same for all users)	LS
Geometry of the cup (radius, height) (same for all users)	GC
Number of users	NUser

Table 4.3. Continued.

System Variables/Parameter	**Reference Name**
Order of commands (with respect to time)	r
Location of the center of mouth of user I (i =1:4)	CMi
Norm of the base of the spoon, user i (i =1:4)	NSi
Norm of the base of the fork , user *i* (i =1:4)	NFi
Norm of the bottom of the cup *m*, user *i* (i =1:4)(m=1:4)	NCmi
Location of the end of the fork handle, user *i* (i =1:4)	EFi
Location of the end of the spoon handle, user *i* (i =1:4)	ESi
Location of the end of the cup *m* handle, user *i* (i =1:4)	ECmi
Orientation of the fork handle (with respect to stationary frame) , user i (i =1:4)	OFi
Orientation of the spoon handle (with respect to stationary frame) , user i (i =1:4)	OSi
Orientation of the cup *m* handle (with respect to stationary frame) , user i (*i* = 1:4) (*m* =1:4)	OCmi
Food tray inner edge geometry for the user *i*	Inedi
Food tray outer edge geometry for the user *i*	Outedi
The path of the fork for all users (array of points)	PF
The path of the spoon for all users (array of points)	PS
The path of the cup m for all users (array of points)(*m* = 1:4)	PCm
Closest distance with any user	CD
Tip: is a vector representing the point that make the closest distance to the user's mouth and the edge or tip of the utensil should reach to that point	tip
Other user waiting time after sending the command	WT
Other user maximum waiting time after sending the command	WTmax
Utensil holding time (for being unloaded)	HT
Utensil maximum holding time (for being unloaded)	HTmax
All the points in the workspace of the robot (considering the constraints)	Workspace
General Command	GComd
General Command with order r, received from user *i*	GComdri

Table 4-4: Acceptable commands from users.

User's Command	Corresponding Programming Command
Pick up the fork for user *i*	PickFi
Pick up the spoon for user *i*	PickSi
Pick up the cup m for user *i*	PickCmi
Go to section k for user *i* (*k* =1:4) (*i* = 1:4)	GoSecki
Hold any utensil (cup, spoon or fork) feeding for user *i*	Holdi
Finish feeding to user *i*	FinishFeedi

Table 4-5: Functions (subsystems) and the reference names.

Function (Subsystem)	Function Name
Image Section Subsystems	
Face recognition of the *i*th user	Ui recog
Recognition of all the objects on the food tray (forks, spoons and cups for all users)	Object recog
Command Section Functions	
Move the arm to the desired end position	MovePd
Gets the commands, and the time and specify the order of command based on their arrival, and the user sending the command and specifying user's waiting time after sending the command	ComdOrder
Grab the handle	GH
Calculate the position of the tip of the spoon/fork/cup	Calc tip
Pick up food with fork from section 3 or 4 and keep it horizontal after picking	PickFood
Scoop food with spoon from section 1 or 2 and keep it horizontal after scooping	ScoopFood

Table 4.5: Continued.

Function (Subsystem)	**Function Name**
Lift the cup *mi* and move in predefined path and keep the cup in horizontal position	LiftCupmi
Calculate the tip position of the fork, spoon, or the edge of the drinking cup	Calc tip
Hold the utensil in calculated tip position and reads the holding time from the timer	Hold
Return the fork from the holding position to the same food section and remove the food from the fork (It assumes that user is refusing to eat and then it waits for the next command)	DumpF
Return the spoon from the holding position to the same food section and remove the food from the spoon (It assumes that user is refusing to eat and then it waits for the next command)	DumpS
Return the cup from the holding position to its original place (It assumes that user is sending the return Cm command and then it waits for the next command)	RtnCm
Return the fork close to the inner edge of the same foods section and get ready to pick up the food	RtnF
Return the spoon close to the inner edge of the same foods section and get ready to scoop up the food	RtnS
Displaying Message Section	
Display message F: ”There is no fork , please insert it or select only from section 1 or 2 in the food tray”	MsgF
Display message S: “There is no spoon, please insert it or select only from section 3 or 4 in the food tray.	MsgS
Display message Cm: ”There is no Cup *m*, choose other cups during the process”	MsgCm
Display message Seck: ”Section k is not been found , please choose from other sections”	MsgSeck

Table 4.5: Continued.

Function (Subsystem)	**Function Name**
Display message “ChooseS” , ”Please choose your food from section 1 or 2”	MsgChooseS
Display message “ChooseF” , ”Please choose your food from section 3 or 4”	MsgChooseF
Display message ”ChooseSecS”, ”Please choose spoon for your food”	MsgChooseSecS
Display message ”ChooseSecF”, ”Please choose fork for your food”	MsgChooseSecF

The fact that the robot is interacting with multiple users, cameras and objects, means some additional tasks must be accomplished, such as managing the received commands from different users and acquired images from different cameras. The procedures that the robot should do to accomplish the required tasks are shown with different flowcharts. These flowcharts in Figures 4-10 to Figure 4-19 make it easier for the system to be programmed.

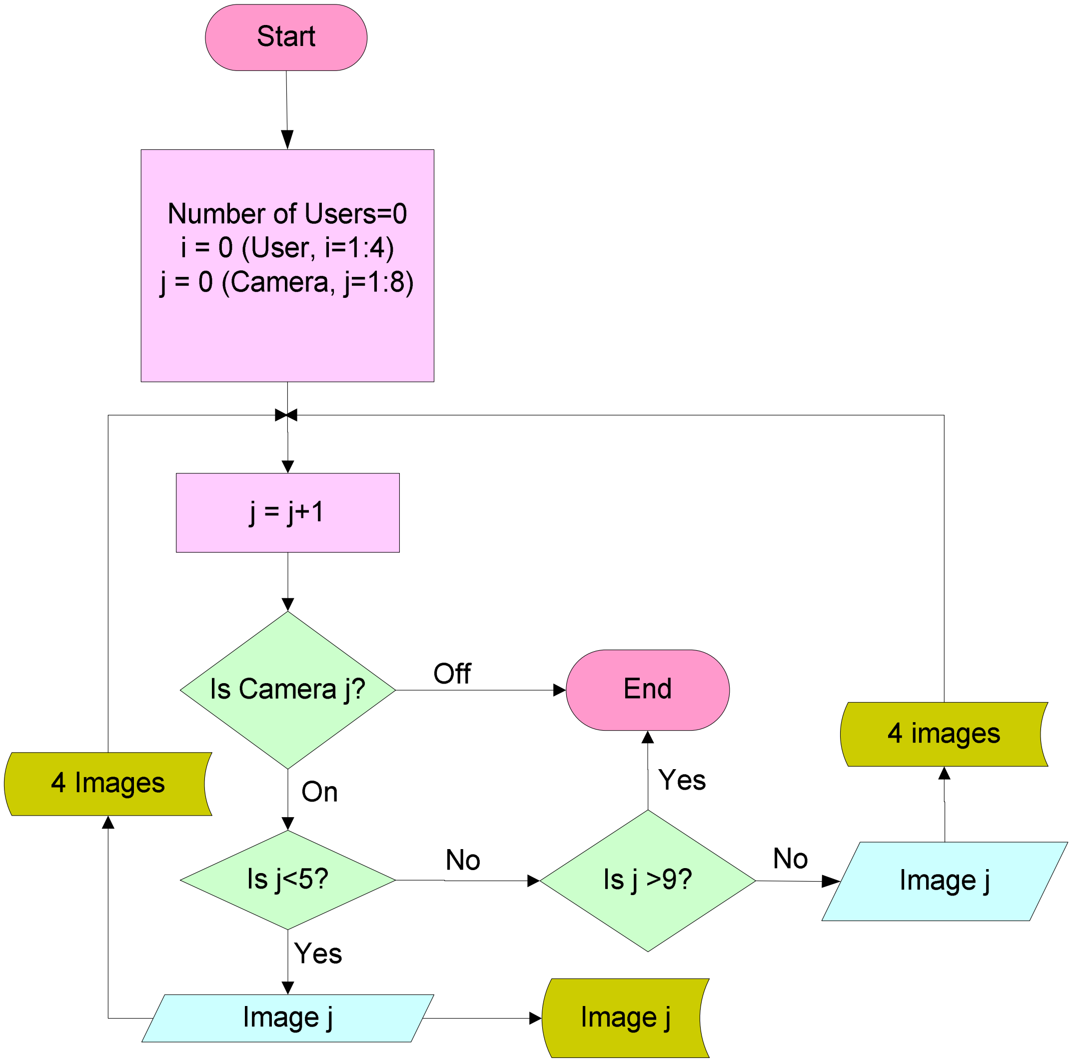


Figure 4-12: Multiple-camera management.

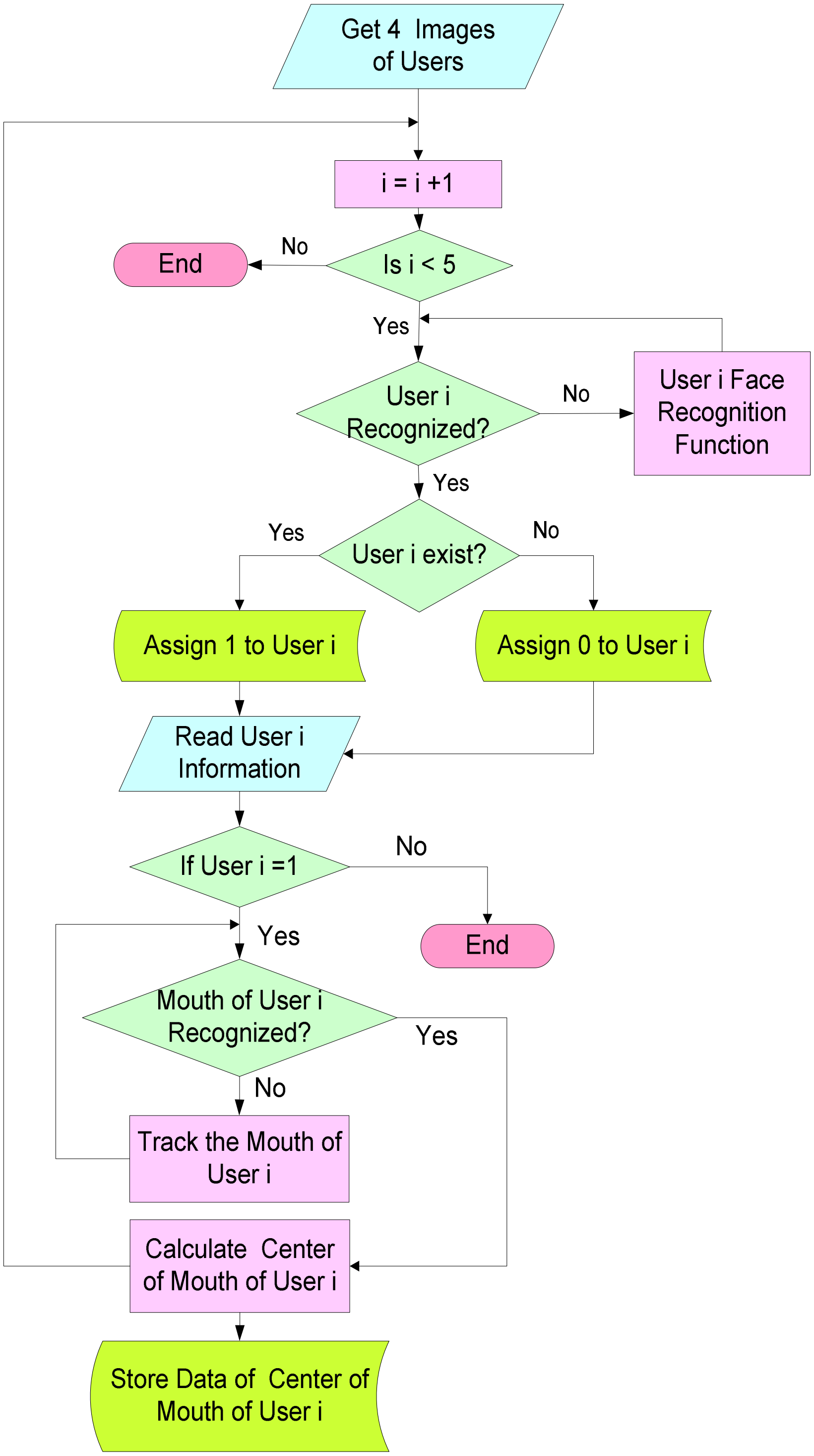


Figure 4-13: User's face recognition and mouth tracking section.

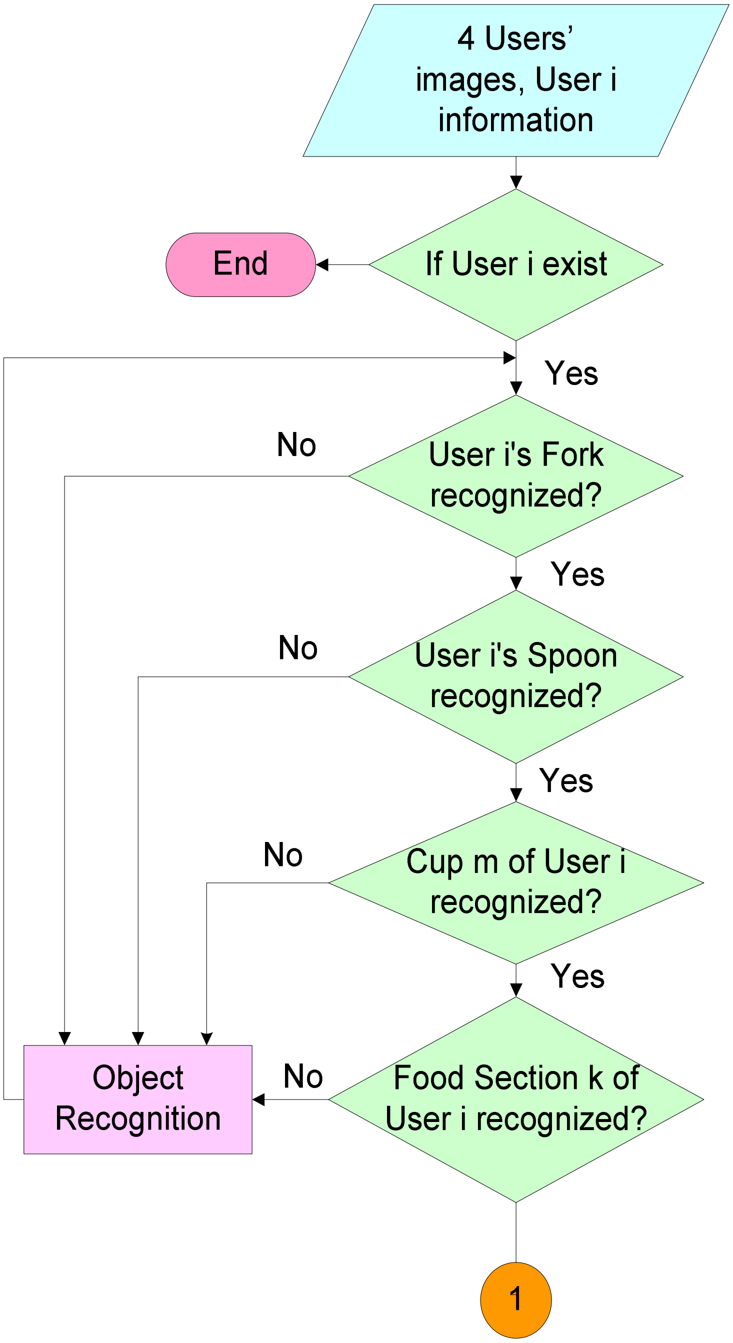


Figure 4-14: Checking the availability of the users and objects, and object recognition section.

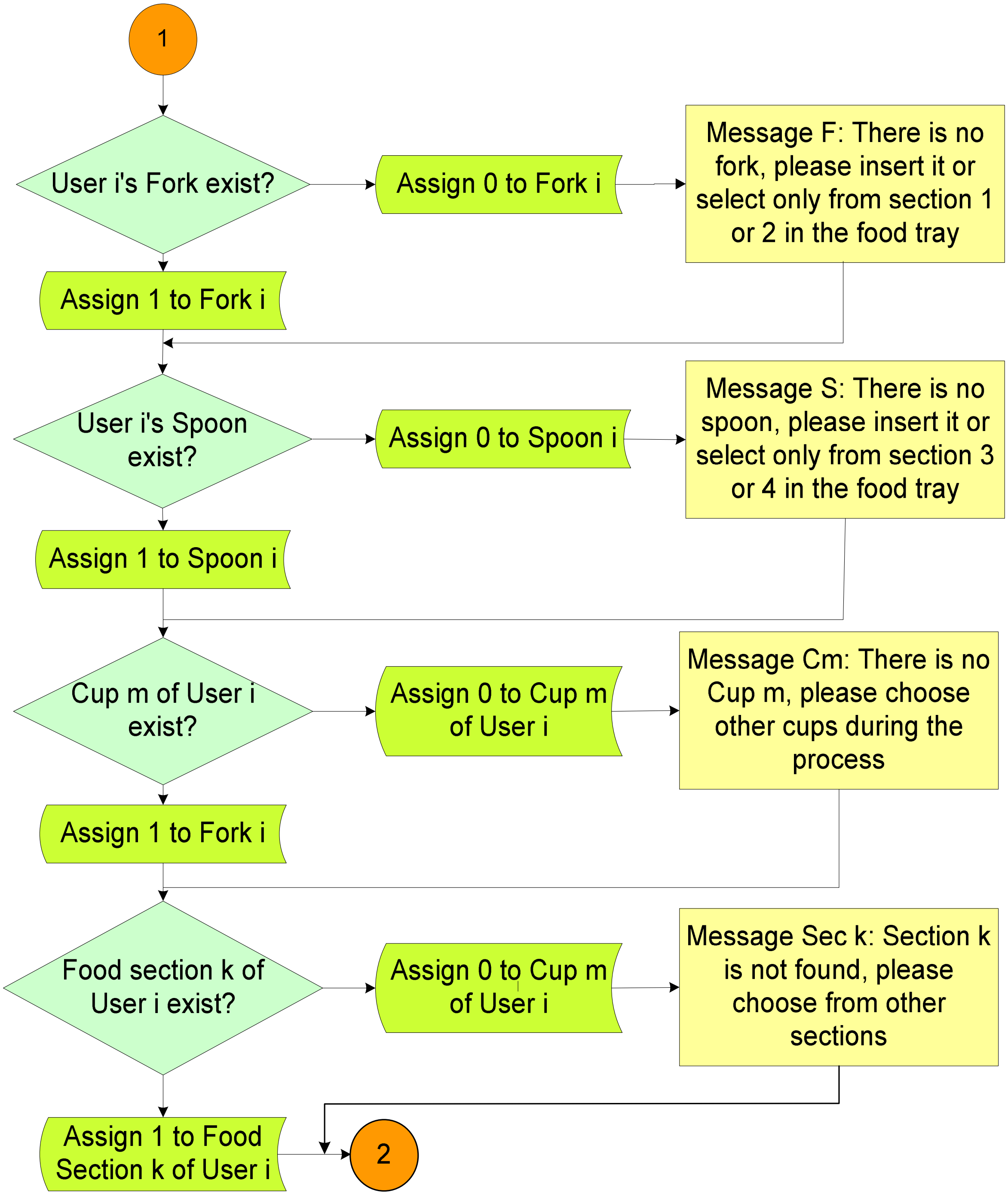


Figure 4-15: Messages sent to the users in case of unavailability of each object.

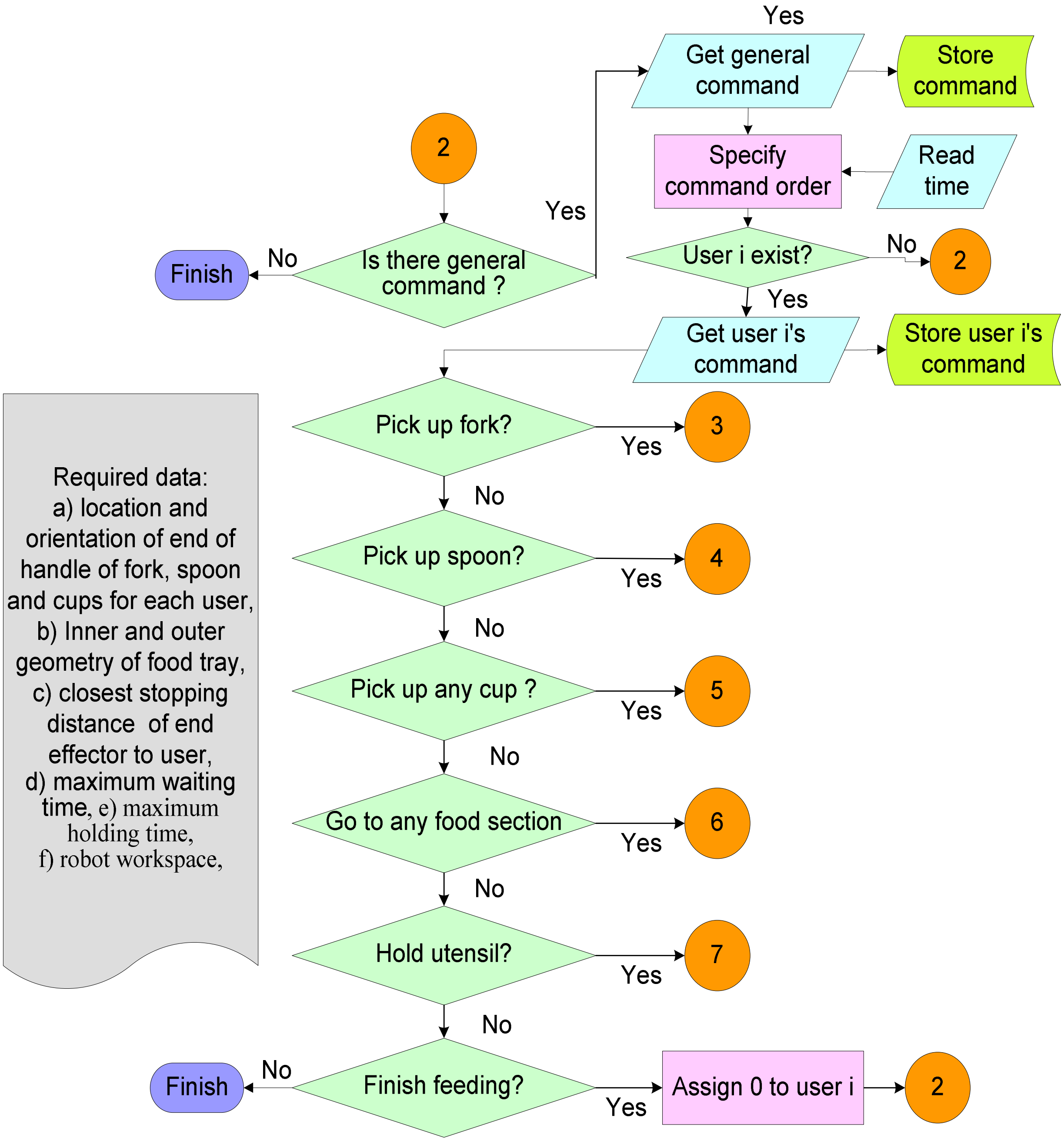


Figure 4-16: Acceptable commands by the feeding robotic system.

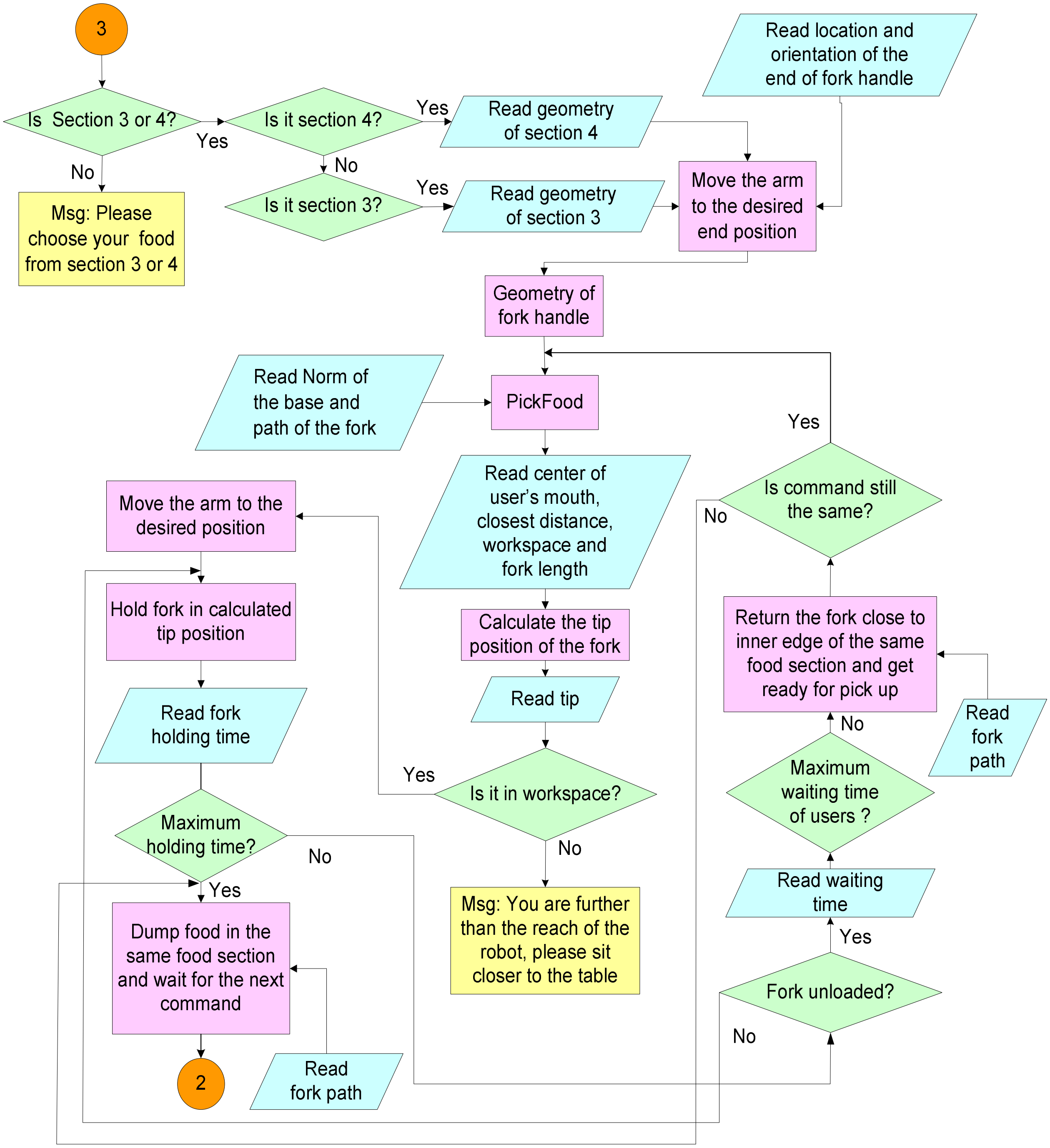


Figure 4-17: Robot's tasks after receiving the command for picking up the fork.

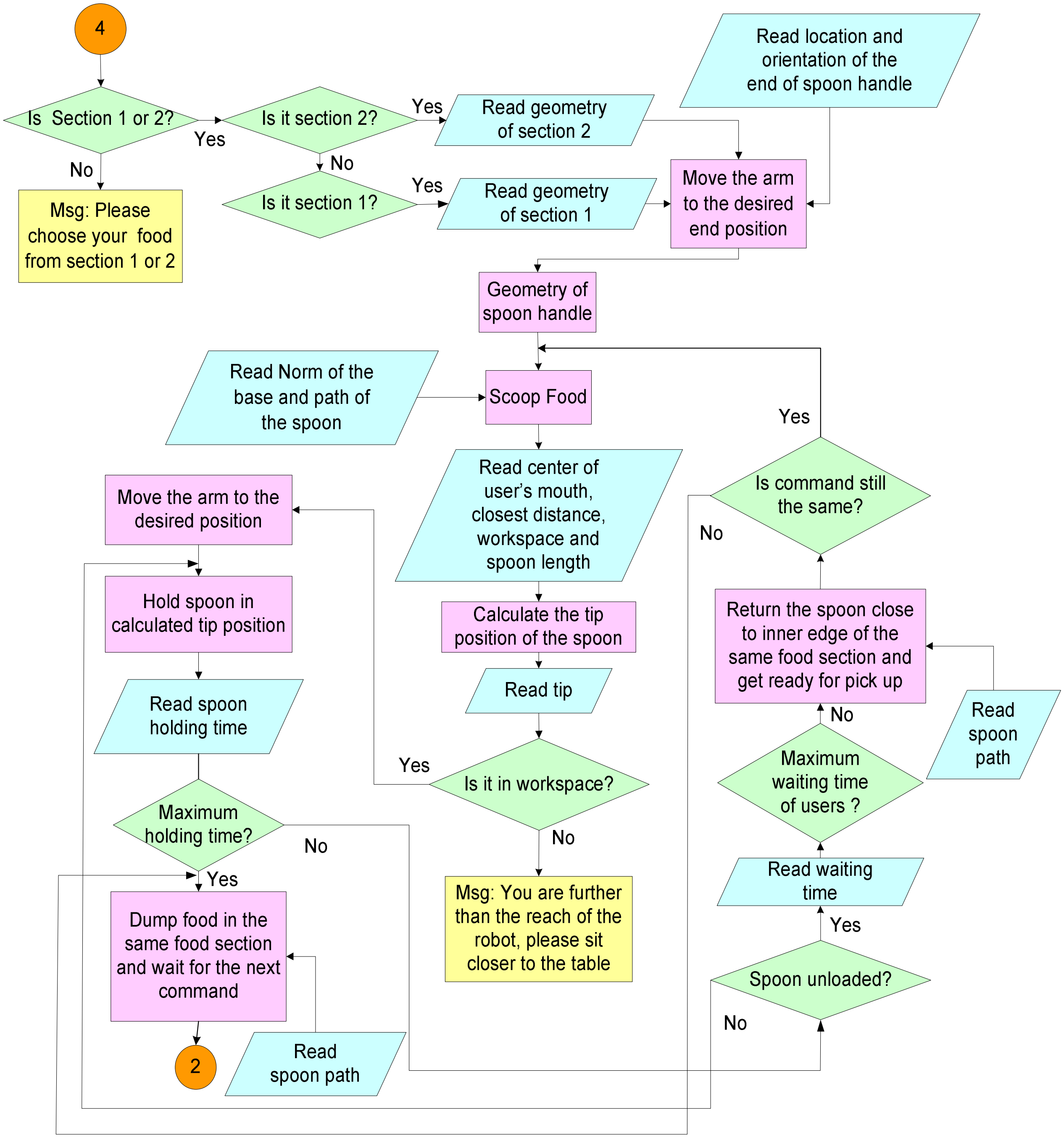


Figure 4-18: Robot's tasks after receiving the command for picking up the spoon.

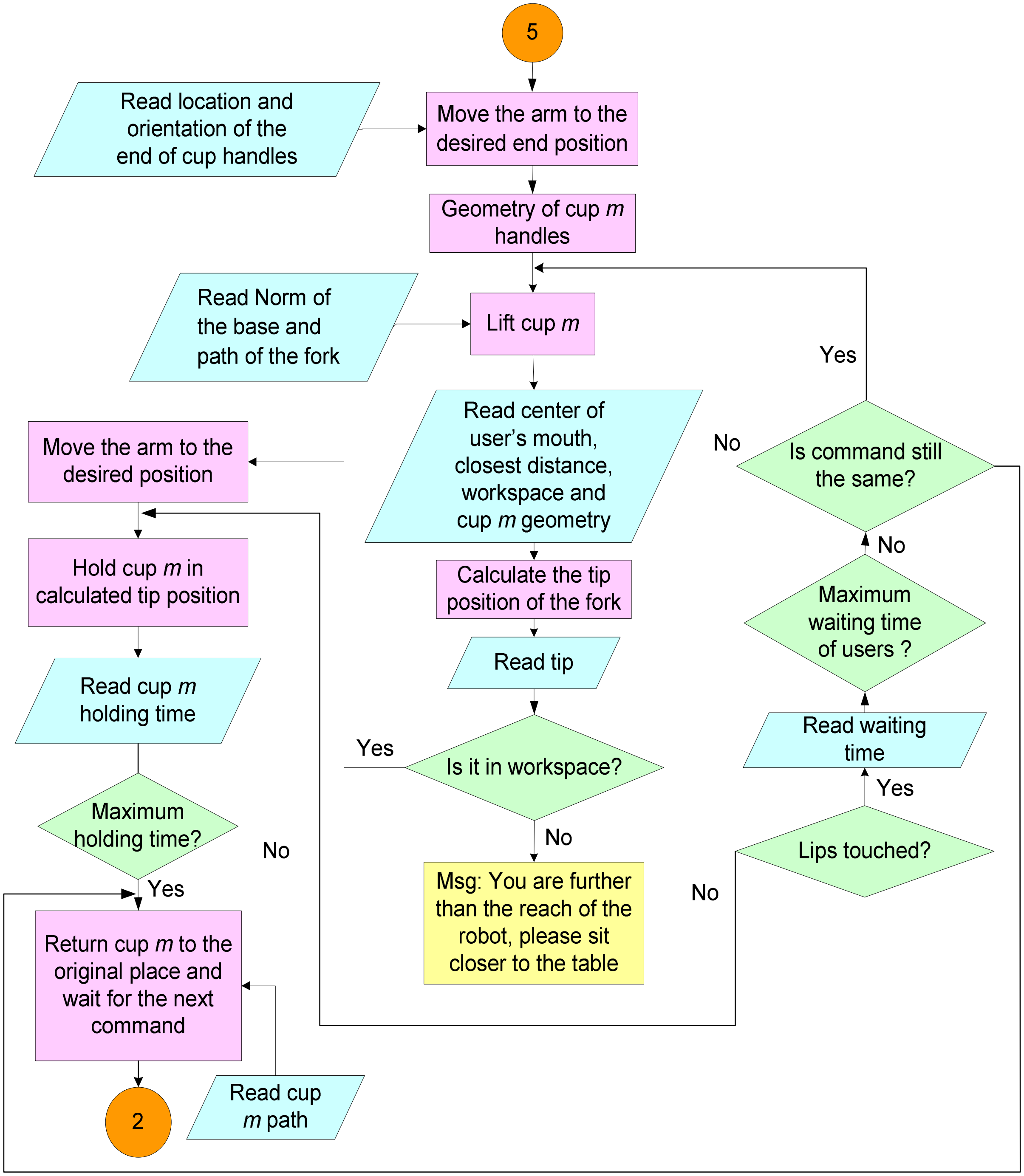


Figure 4-19: Robot's tasks after receiving the command for picking up any of the cups.

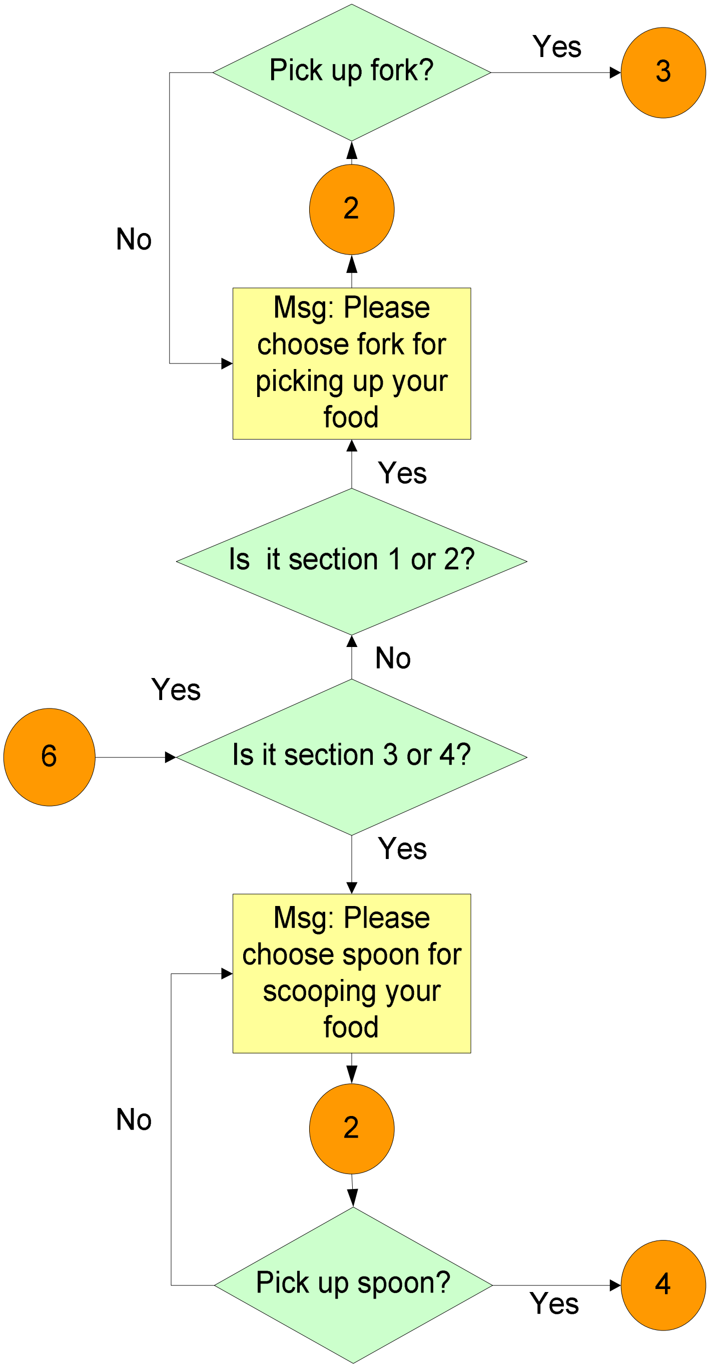


Figure 4-20: Messages sent to the users for choosing an appropriate utensil for picking up the food according to the chosen section of food.

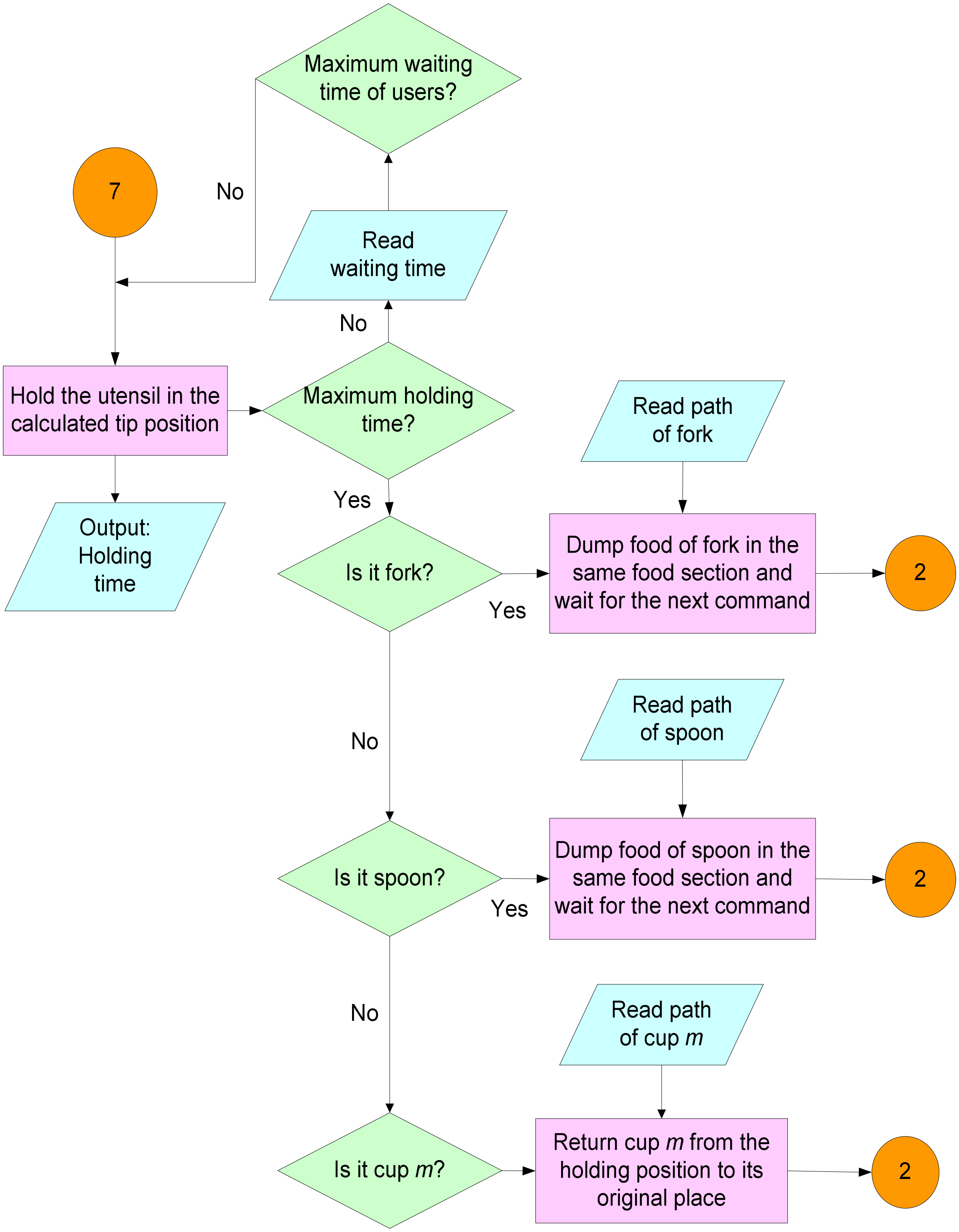


Figure 4-21: Robot's tasks after receiving the command for holding any of the utensils.

The next chapter explains the kinematics and dynamics of the system. In the kinematic section, the transformation matrices are found and the inverse problem is discussed. The dynamic section provides the related information and data when the robot is in action, such as velocities and accelerations of the links, joints and desired specific points. It also discusses the singular positions of the system that should be avoided. The control system section provides details regarding position control of the end effector on the desired path.. The control procedures are done with the help of ADAMS control and Matlab 7.2 to control the path of the end effector in a virtual environment.

Chapter 5

Kinematic, Dynamic and Control of Multiple-User Feeding Robot

5.1 Kinematic and Inverse Problem

In problems of forward kinematics, a mapping from joint space to Cartesian space is performed; however, in inverse kinematic computation, the robot joint angles of the links are found from a given Cartesian position and orientation of the end-effector. While, the forward kinematic solution gives the coordinate frame, or pose, of the last link, the inverse kinematic solution is more useful for path planning of the manipulator, motion control and workspace analysis [59]. This inverse problem is particularly fundamental for general serial manipulators, which are controlled by computers [60]. However, their equations may not be easily solved, since the system is coupled and may also be nonlinear and have multiple solutions. For the general case of a 6-DOF arm, the solution of a 16th order polynomial equation is required [61].

The iterative solutions, based on numerical techniques, for general 6R manipulators have been known for quite some time. There are basically two types of these numerical methods: the first type uses the Newton-Raphson method to solve the non-linear equations to integrate the differential kinematic equations. The problem with these methods is that when the Jacobian matrix is singular or ill-conditioned it fails to find any solution. The second type is based on optimization techniques, which, instead, solve an equivalent minimization problem to provide a numerically more stable method. One of the approaches in the second type, in [59], is based on the combined optimization that finds the feasible point near the true solution, and obtains a solution at the desired degree of precision, to make it insensitive to the initial or singular configuration of the manipulator.

However, two drawbacks of the numerical techniques are an inability to find all the solutions [59] and that they are too slow for practical applications. Pieper [62] proved that if manipulators have three consecutive joints with collocated frames, a closed-form inverse position solution exists. To lessen the amount of calculation and to ensure closed form solutions, it is possible to arrange the last three joints in such a way that they meet the criteria specified by Pieper. In the case of the selected manipulator in this project, the 6-DOF CRS robot is chosen because all of the axes of the three wrist joints intersect at one point. This simplifies the equations and reduces the problem to one that has a closed form second order solution.

For the forward kinematic problem, the Denavit-Hartenberg table is used to model the 6R manipulator and to develop the transformation matrices. The results are summarized in Appendix C.

5.1.1 Analysis of Manipulator Singularity

Singular configuration should be considered in task planning and robot control [63], since one or more degree/s of freedom is/are lost due to singularities. The singularities of non-redundant manipulators are found from the determinant of the manipulator Jacobian matrix **J** which relates joint velocities to spatial velocities [64]. The sets of angles of the joints which result in zero or near zero determinants are at or near singular configurations which cause the joint rates to become extremely large, often exceeding the physical limits of the actuators. Therefore, singularities create serious problems for the execution of spatial tasks [65]. There are two types of singularities: structural and kinematic [63]. While structural singularities are independent of the joint variables, depending only on the manipulator architecture, kinematic singularities are dependent on the joint variables (finite displacement of the joints) in any given manipulator architecture. Infinite joint rates are required to maintain finite end-effector velocities when motion planning is done improperly so that the end effector is commanded to move in a way to avoid the singularity [63].

Some of the past approaches to solve the problem are: 1) pseudoinverse technique using the damping factors to limit feasible joint rates in the vicinity of a singular configuration by allowing some deviations of the end-effector trajectory; 2) identifying the degenerated direction of motion associated with singular positions and avoiding motion in that direction; 3) truncating the high joint velocity by eliminating the linearly dependent columns and rows from the Jacobian matrix; 4) separating the dependent and independent motions; 5) using the alternative velocities to replace unfeasible desired velocity specifications; 6) robot-motion parameterization; 6) singularity-robust trajectory generation based on time-scaling; 7) workspace transformation; and 8) bordered matrix method [66].

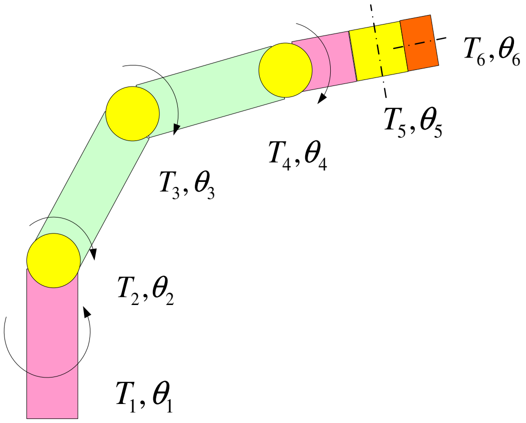


Figure 5-1: 6-DOF robot, inputs and outputs.

If the joint angles are defined as shown in Figure 5-1, the simplified form of the Jacobian matrix for the selected 6-DOF serial articulated manipulator is:

$$\mathbf{J}=\begin{bmatrix} s_1(c_{23}l_c+c_2l_b) & -c_1(s_{23}l_c+s_2l_b) & -c_1s_{23}l_c & 0 & 0 & 0 \\ c_1(c_{23}l_c+c_2l_b) & s_1(s_{23}l_c-s_2l_b) & s_1(-s_{23}l_c) & 0 & 0 & 0 \\ 0 & c_{23}l_c+c_2l_b & c_{23}l_c & 0 & 0 & 0 \\ 0 & s_1 & s_1 & s_1 & c_1s_{234} & -c_1s_5c_{234}+s_1c_5 \\ 0 & -c_1 & -c_1 & c_1 & s_1s_{234} & -s_1s_5c_{234}+-c_1c_5 \\ 1 & 0 & 0 & 0 & -c_{234} & -s_{234}s_5 \end{bmatrix} \quad (5\text{-}1)$$

where:

$$\mathrm{s_i} = \sin\theta_i \text{ and } i = 1,\ldots,6 \qquad (5\text{-}2)$$

$$\mathrm{c_i} = \cos\theta_i \text{ and } i = 1,\ldots,6 \qquad (5\text{-}3)$$

$$\mathrm{s}_{23} = \sin(\theta_2 + \theta_3) \qquad (5\text{-}4)$$

$$\mathrm{c}_{23} = \cos(\theta_2 + \theta_3) \qquad (5\text{-}5)$$

$$\mathrm{s}_{234} = \sin(\theta_2 + \theta_3 + \theta_4) \qquad (5\text{-}6)$$

$$\mathrm{c}_{234} = \cos(\theta_2 + \theta_3 + \theta_4) \qquad (5\text{-}7)$$

The determinant of the Jacobian matrix after simplifications is:

$$\det(\mathbf{J}) = \mathrm{l_b l_c s_3 s_5 (c_{23} l_c + c_2 l_b)} \qquad (5\text{-}8)$$

In the singular positions the above determinant should be equal to zero. $\det(\mathbf{J}) = 0$. Since $\mathrm{l_b}$ and $\mathrm{l_c}$ are not zero, any of the three cases may lead to the singular positions:

$$\mathrm{s}_3 = 0 \qquad (5\text{-}9)$$

$$\mathrm{s}_5 = 0 \qquad (5\text{-}10)$$

$$\mathrm{c_{23} l_c + c_2 l_b} = 0 \text{ or } \frac{\mathrm{c}_{23}}{\mathrm{c}_2} = -\frac{\mathrm{l_b}}{\mathrm{l_c}} \qquad (5\text{-}11)$$

This implies that in either of the following joint angles, the robot arm is in a singular position:

$$\theta_3 = 0\ ,\ \theta_3 = 180^\circ,\ \theta_3 = -180^\circ \quad (5\text{-}12)$$

$$\theta_5 = 0,\ \ \theta_5 = 180^\circ,\ \theta_5 = -180^\circ \quad (5\text{-}13)$$

$$\theta_2 + \theta_3 = \cos^{-1}(-\frac{l_b}{l_c} c_2)\,, \text{ where } \theta_2 \neq +90^\circ, -90^\circ \quad (5\text{-}14)$$

Since the range of motion for joint 3 is $\pm 110^{\circ}$ (in Appendix C), from the singular conditions shown in Equation 5-12, only $\theta_3 = 0$ leads to a singularity. Similarly, the range of motion for joint 5 is $\pm 105^{\circ}$ and from the possible singular position for this joint represented in Equation 5-13, only $\theta_5 = 0$ results in a singularity for this robot. However for the second joint, with $\pm 90^{\circ}$ range of motion, the internal singularity, as presented in Equation 5-14, happens exactly at or in the vicinity of $\theta_2 = +90^{\circ}, -90^{\circ}$, which is better to be avoided.

To avoid the singularities, the ranges of motion defined by the user's manual will be modified slightly by considering the singular angles and conditions.

5.2 Building Dynamic Equations

The robotic system has 6-DOF that receives six torques as inputs and sends six joint angles as outputs. The schematic system has been presented in Figure 5-1. In order to attain the dynamic equations of the system, a system with similar characteristics was built in the Maple environment DynaFlexPro (DFP) toolbox. DFP is a collection of Maple routines [67] that can automatically generate the symbolic equations of motions for the proposed multi-body system. DynaFlexPro is used to automatically generate the dynamic equations in terms of the coordinate system [67]. A system model was built inside the Model Builder (MB) environment by assembling the block diagram representation. The model of the 6-DOF robot made in MB is shown in Appendix E.

Rigid bodies are represented by blocks and joints by arrows. The arrows connect reference frames that are fixed on each body, which are shown as circles on the bodies to which they are affixed. The position and orientation of any other frame on the body is defined relative to this primary reference frame. After saving the system model in a DynaFlexPro input file, both kinematics and dynamic equations of the system were generated. In the model, all the generalized coordinates are independent, and dynamic equations governing the system response constitute a set of ordinary differential equations (ODEs). The ODEs for the dynamic response can be solved simultaneously with nonlinear algebraic equations.

After formulating the system equations, a step forward in simulating kinematic, inverse dynamic and forward dynamic equations was taken. Maple uses built-in numerical routines (e.g. fsolve, dsolve) to solve these equations for the time response of the system [67]. The complete descriptions of the DynaFlexPro input model generated by MB, is in Appendix D. This *.dfp* file was exported to Maple for generation of the equations.

5.2.1 Behaviour of ADAMS Model to the Given Motions

The graphs for angular and translational displacements, velocities and accelerations of each joint and moving part of the simulated robot, including the torques and forces at joints, and their kinetic and potential energies, are extracted from ADAMS simulation. Figure 5-3 to Figure 5-9 show some part of the results of the model behaviour. The rest of the results are presented in Appendix F.

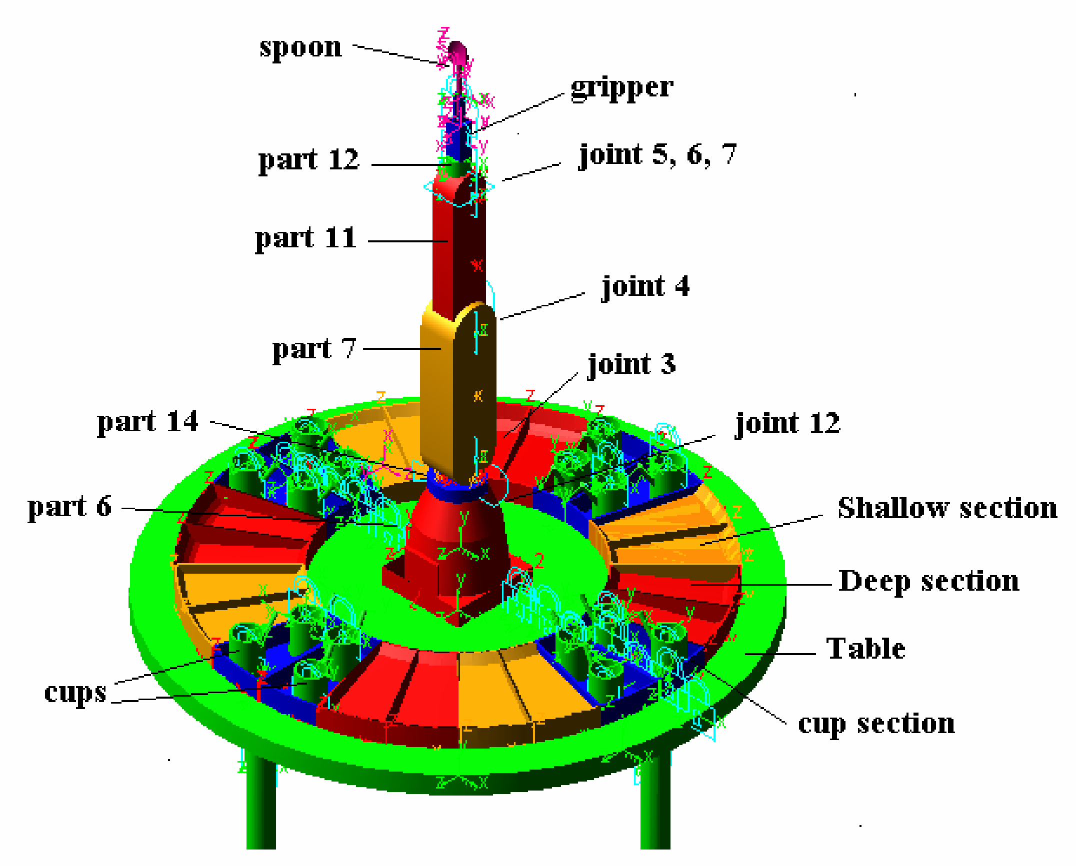


Figure 5-2: Specification of part numbers for dynamic analysis.

Motion_1 attached to Joint_3 (between part_14 and part_7)

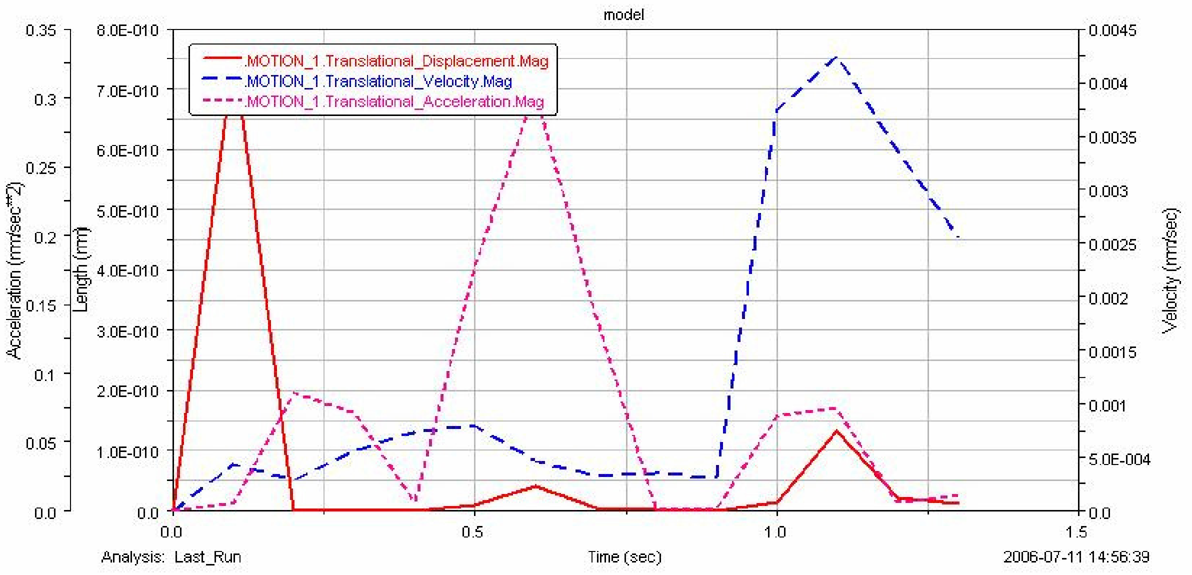


Figure 5-3: Magnitude of the translational displacement (continuous line), translational velocity (dashed line) and translational acceleration (dotted line) for Motion 1.

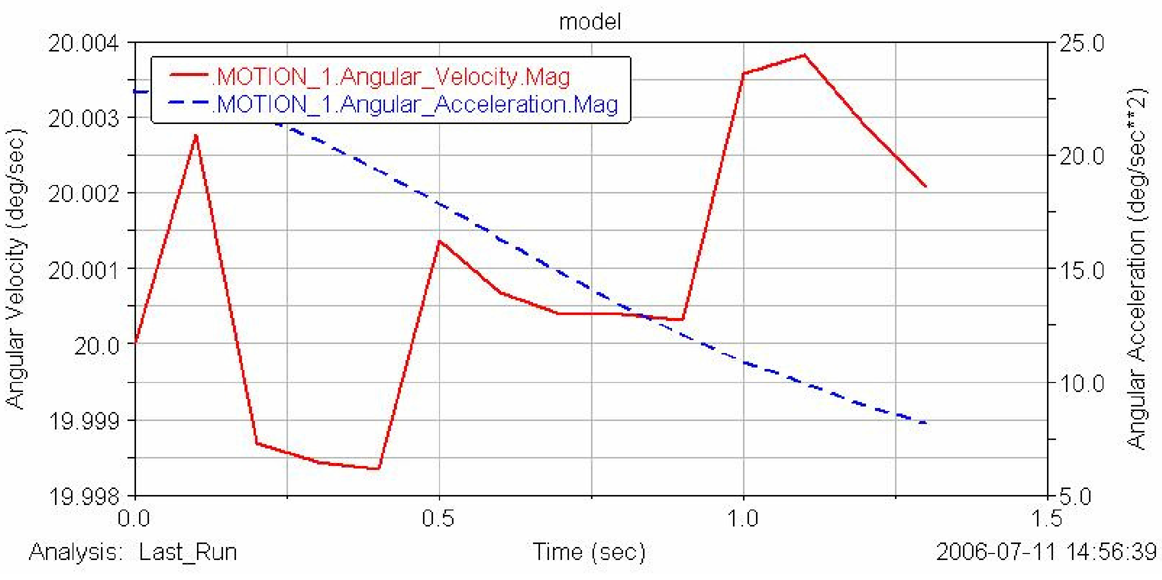


Figure 5-4: Magnitude of angular velocity (continuous line) and angular acceleration (dashed line) for Motion 1.

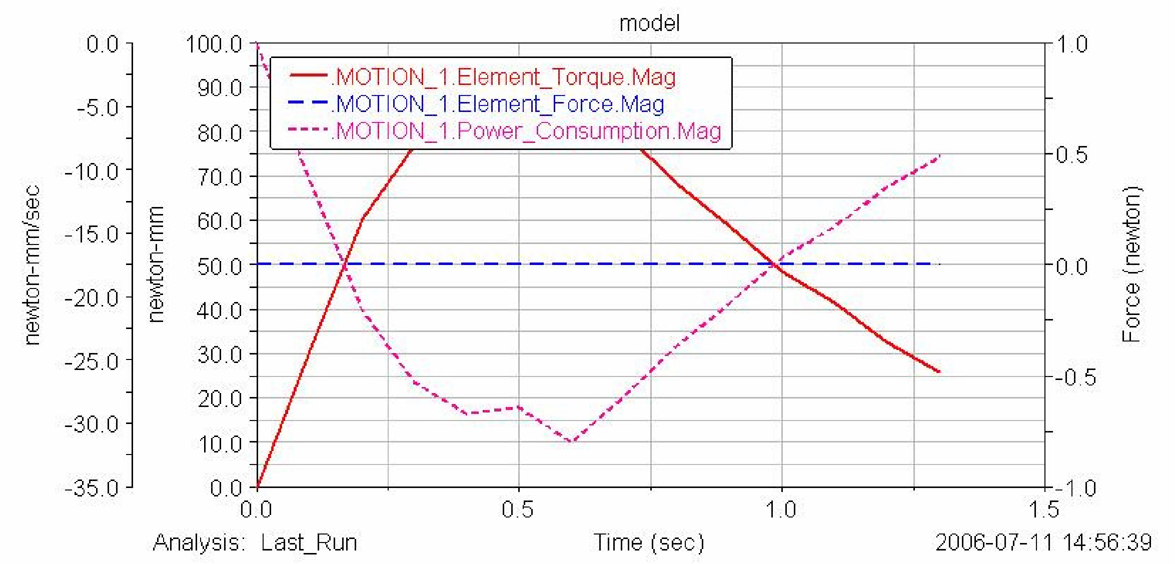


Figure 5-5: Magnitude of the element torque (continuous line), element force (dashed line) and power consumption (dotted line) for Motion 1.

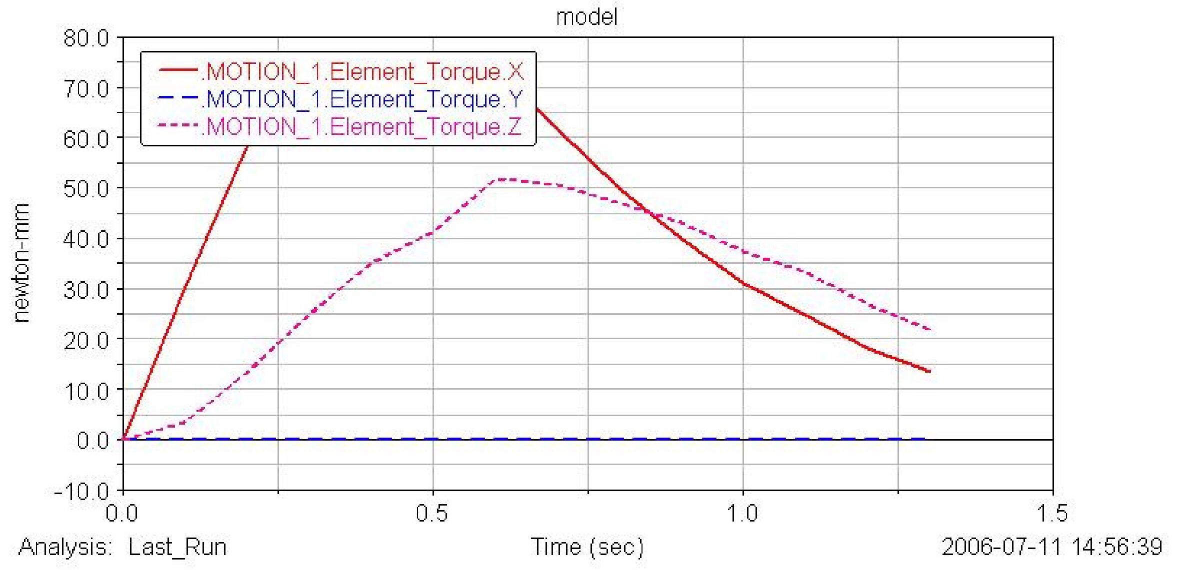


Figure 5-6: The x (continuous line), y (dashed line) and z-components (dotted line) of the element torque for Motion 1.

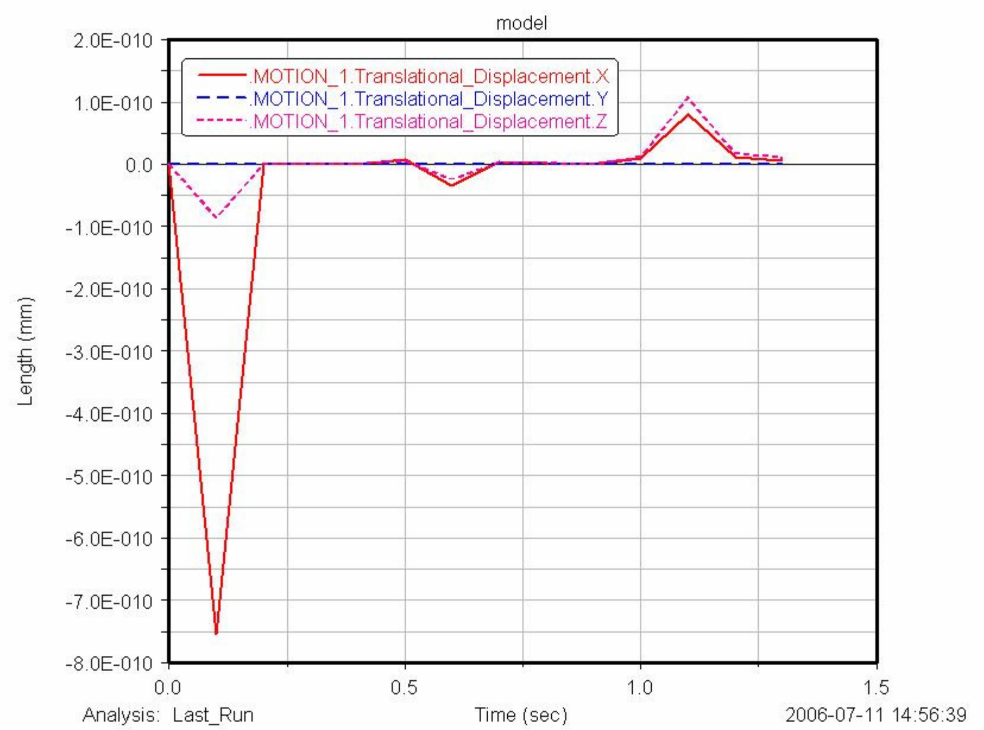


Figure 5-7: The x (continuous line), y (dashed line) and z (dotted line) components of the translational displacement for Motion 1.

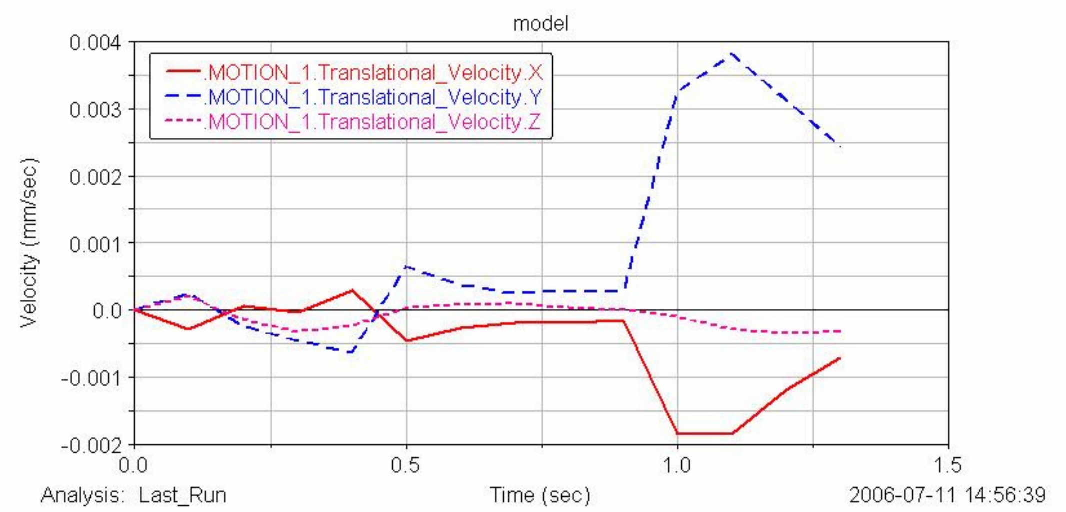


Figure 5-8: The x (continuous line), y (dashed line) and z components (dotted line) of the translational velocity for Motion 1.

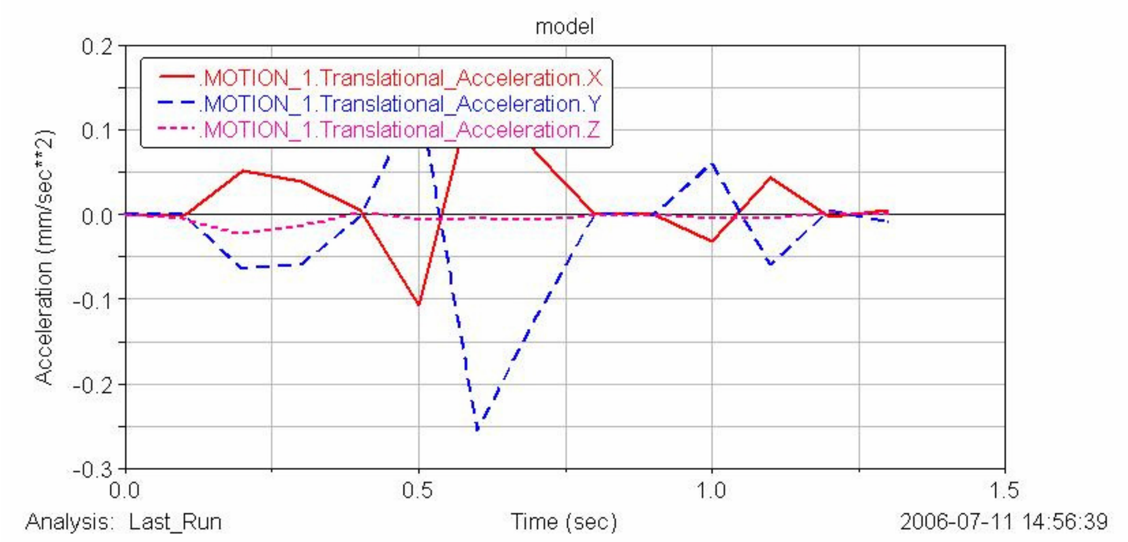


Figure 5-9: The x, y and z components of the translational acceleration for Motion 1.

5.3 Robot Control

The robot control problem can be divided into two main areas: kinematics, which takes care of the coordination of the links of the kinematic chain to produce desired motions of the robot, and dynamic control, which drives the actuators of the mechanism to follow the commanded positions/velocities. To give some autonomy to the robotic arm within an unstructured environment, the robot should be able to identify potential problems in its environment and implement limited responses in real time [68]. The control of robots that are designed and employed in the service of humans, has to handle the problems related to human-robot interaction. The most important issues are [69]: 1) guaranteeing safety in shared unstructured environments, to prevent possible injuries, and 2) resolving the contact and touch problem with the human, and 3) avoiding self-collision.

For an activity that requires force in measurement and control, in addition to position control, compliance is necessary. An example of this is a task where movement continues until contact is made with a surface, and constrained motion follows. Compliance is actually important in planning fine motion strategies. Compliance is required when the robot is constrained by task geometry, or when the robot is in contact with its environment. It can be achieved by active or passive means. Active compliance control relies on a force sensor and an algorithm to move the robot according to force sensor readings. Passive compliance is needed to overcome the limited position resolution and to enhance the disturbance rejection capabilities [70].

Compliance is undoubtedly a first step in ensuring safety when workspace sharing is allowed, but it is particularly useful in facilitating effective human-robot interactions that permit physical contact and cooperation. Eating action requires adaptability of robot positioning to the user movements; to the relative position between the user's body and the robot arm, as well as to the shape and the current position of their body parts, depending on the specific task. In designing the control of human assistive robots, three important considerations are: safety, human-robot interaction, and functionality. Then the goal is to find the best trade-off between safety and effective human robot interaction and accurate execution of the tasks [71].

Service robots are designed to live among humans, to be capable of manoeuvring in human-oriented environments and to have substantial autonomy in performing the required tasks in such complex environments. They must coexist with humans who are not trained to cooperate with robots and who are not necessarily interested in them. Safety must be guaranteed with these robots, since they are in the presence of humans in the same work space [72]. The method of collision free planning for industrial robots, which is based on previous knowledge of the environment, is not applicable in unstructured situations [73]. The non-contact obstacle avoidance approaches [74-76], based on optical, ultrasonic and proximity sensors can improve human safety, but may also suffer from problems with dead angles, disturbances as well as poor image processing capabilities and ambiguity of detectable volume in proximity sensing techniques. High reliability may not be achieved with these sensors. Other methods for safety improvement have been developed, such as impedance control (covering the robot body with viscoelastic material) [77], use of a mechanical impedance adjuster equipped robot with linear springs and brake systems [78], robots with flexible joints [79], compliant shoulders [80], and viscoelastic passive trunks [81]. Addressing these safety issues is beyond the scope of this thesis.

5.3.1 ADAMS Control

In this part, it was intended to import an ADAMS model, run a trial simulation with ADAMS/View and use the ADAMS/Controls interface to identify the inputs from the ADAMS model and then create files for a plant model in Matlab/Simulink. In addition, it was intended to add a control system to the robot-end effector that would move the end effector along a defined path to track the user's mouth or to approach a recognized food part. The torque that pivots the robot joints was supplied. The torque level was computed by a control system, based on the error between the actual end effector position and its desired position. Figure 5-4 describes the process of combining control with a mechanical system.

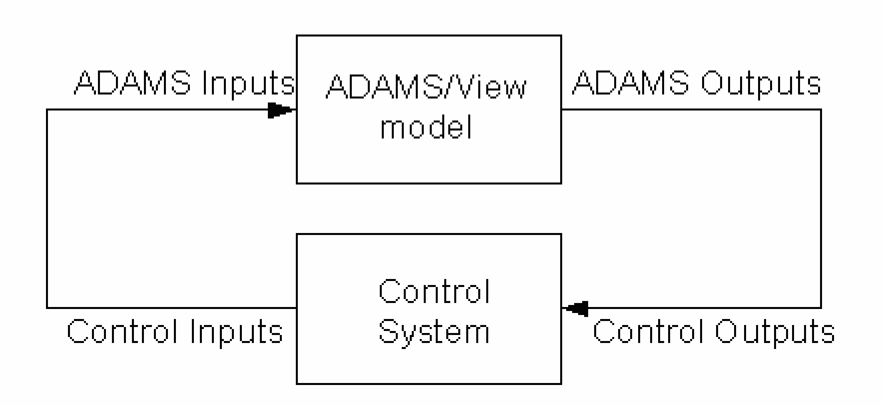


Figure 5-10: ADAMS Model and Control System versus their input and output [ADAMS].

After loading the ADAMS/Controls plug-in in ADAMS/View, the model was imported, ADAMS control was loaded, and the trial simulation was run. Then the motions on the model were deactivated and the torques applied to the joint, based on values that the control-system package provides.

In the second step, the ADAMS plant inputs and outputs were identified. When an input control torque was supplied to the robot model, the output position and velocity was sent to the controller. Then to achieve the closed-loop circuit, it was necessary to define the input and output variables in ADAMS/View, read in the plant and input/output variables using MATLAB, and create a MESC.ADAMS plant and run a simulation. The simulation results in ADAMS /View were animated and plotted and the variables were modified and the process was repeated as many times as necessary. Then after all these procedures, ADAMS/Controls saved the input and output information in an .m (for MATLAB) file. It also generated the command files (.cmd) and dataset files (.adm) that were used during the simulation process. ADAMS/Controls setup was complete after the plant files had been exported. Then the link between the controls and mechanical systems was completed by going through the specific controls application (MATLAB).

In the third step, control was added to the ADAMS block diagram using MATLAB. In MATLAB a new model in Simulink, was made which contains the S-function block of the MSC Software that represents the mechanical system of the feeding robot. The S-function represents the nonlinear ADAMS model and state-space block represents a linearized ADAMS model. Names automatically match up with the information read in from the .m file. The adams_sub contains the S-Function, but it also creates several useful MATLAB variables. The defined input and outputs of the model appear in the sub-block. The sub-blocks, created based on the information of .m file in MATLAB, and I/O of the model, along with ADAMS/MATLAB interface are represented in Appendix G.

Using the Simulink in MATLAB and existing adams_sub block a new model was created, as shown in Figure 5-11, and the simulation results appear in Figure 5-12.

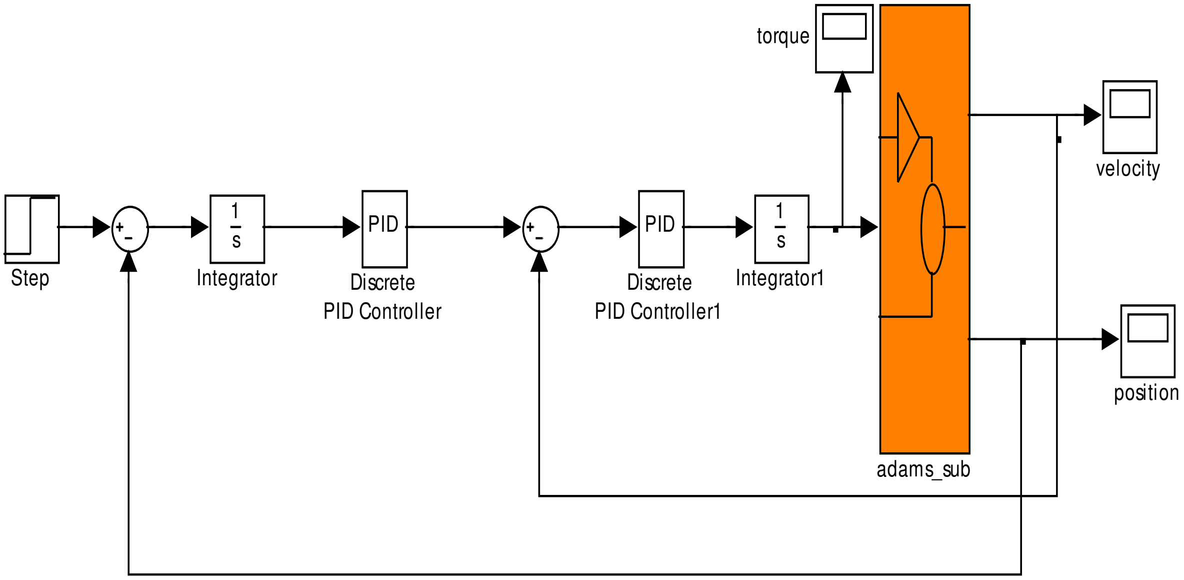


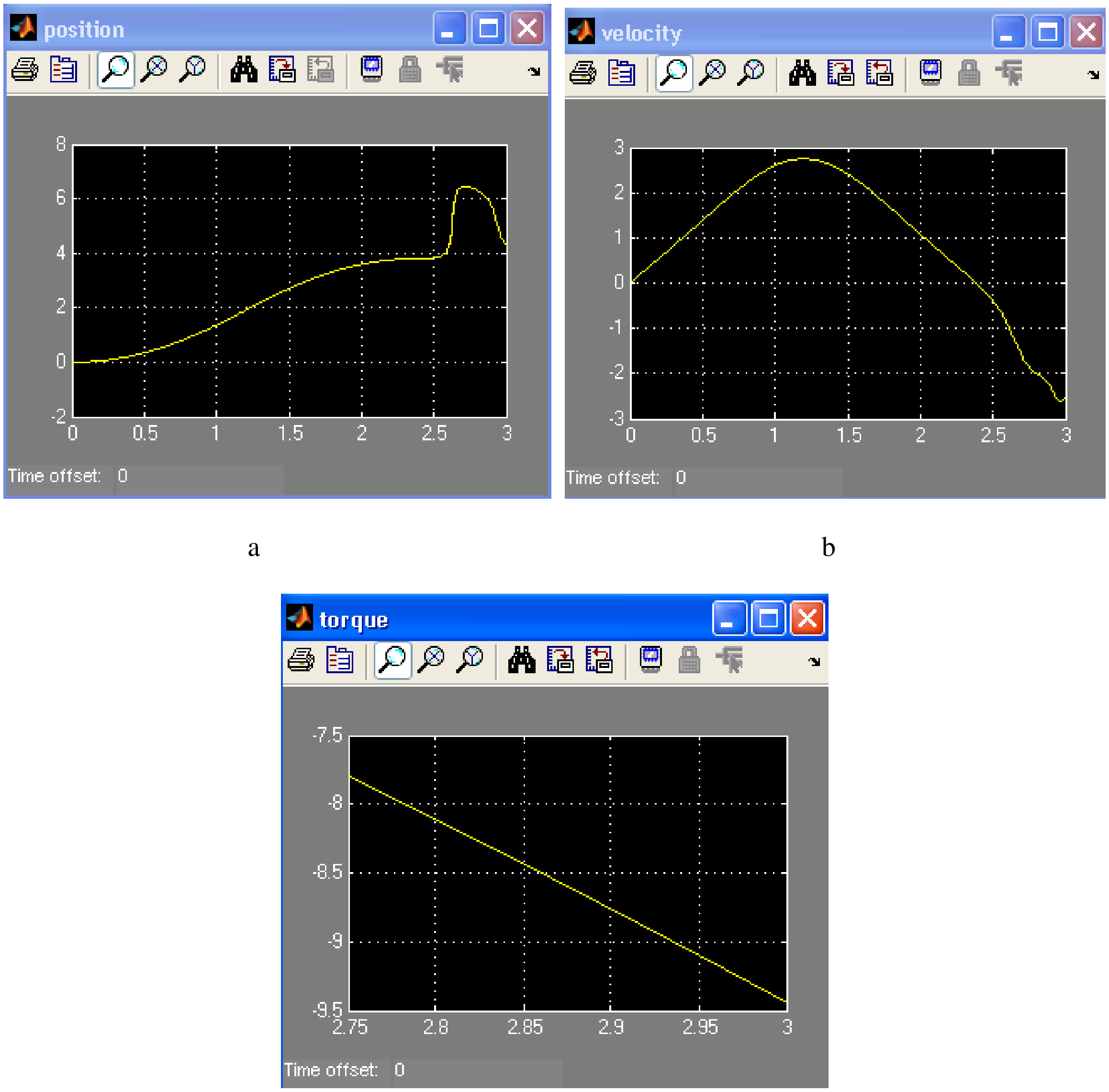
Figure 5-11: Simulink model for control block.

The simulation parameters were set as follows:

Solver options: Type: variable-step

Solver: ode45 (Dormand-prince)

Relative tolerance: 1e-3



a

b

c

Figure 5-12: Simulation results a) position of the end effector (mm) b) output velocity (mm/s) and c) input torque (N-mm).

The next chapter justifies the use of vision system as the interface of the feeding system, and then it discusses the different approaches available for processing the acquired images and the effect of their application. All the processing is performed on food images because at present, this project is not dealing with face recognition of the potential users. It is assumed that the user's mouth locations are known for now. In the future, the results of face recognition will be replaced with the data currently assumed.

Chapter 6

Vision System and Image Processing

6.1 Rationale for the Use of Vision System

The vision system is one of the interfaces that does not suffer any interference from or conflict with the disabilities of users. That is, the probability of system failure stems solely from the program used, the environmental lighting conditions or the background color, not the users. In this thesis, it is assumed that the use of buttons/switches send the user's commands to the robot, and the integrated vision system is used for recognizing the position of solid foods inside the flat sections of the food trays and checking for the presence of cups and utensils in their places.

The fact that the proposed feeding robot uses a vision system to find the location of solid food parts inside the tray by itself suggests that it is intelligent. Ultimately, it is intended that the proposed robot be capable of attending to multiple users with various disabilities by providing the option of different user interfaces. However, at the present time it is necessary to limit the robot's capabilities and user interfaces to ensure that the overall system works in a simplified form.

The proposed vision system, shown in Figure 4-8 and discussed in Section 4.8, would acquire many images from the food trays and the users' faces (the latter is not addressed in detail here). The food tray images are used for: 1) segmenting and recognizing each piece of solid food inside the flat plate and finding the centers of each piece (the fork will be inserted into this point to pick up the piece); and 2) checking the presence of the cups and utensils in their places (it is assumed that their location and shapes are already fixed and known).

Since it is assumed that the food inside the deep plates are soft, with no specific shape or differentiability, they may not be easily segmentable or recognizable in the image and therefore, no image information regarding that section will be processed. The spoon moves in a predefined smooth path to sweep through the deep section of the plate and scoops up the food. Visual information then specifies the location of the closest safe point to the user's mouth where the robot's end effector should stop. At the present time, the developed image processing system in Matlab is able to recognize and specify the fork insertion points for the pieces of cut toast and sandwiches with acceptable accuracy.

6.2 Vision Related Tasks

The feeding robot task is divided into two parts. The first part, is a pick-and-place type operation in a constrained environment, where total knowledge of the relevant objects to be manipulated is assumed to be known. Some of the objects to be manipulated in this part are the spoon, the fork and the cups. This means that the robot knows the vicinity of its approach and the exact location and orientation of the objects. In a pick-and-place operation, the objects are always in a previously known, absolute position and orientation. This approach offers little flexibility.

The second part consists of an active system which uses sensory or visual feedback to understand the environment. The work environment in this case is non-static and unconstrained. Some of the objects which should be recognized are different pieces of solid foods that are not necessarily placed in the same position and orientation in the food tray sections. Incorporating feedback into the system allows non-determinism to creep into the deterministic control of the robot. The challenge is to incorporate these sensors into a system and to make use of the data provided by them.

The main purpose of this part of the work is to improve the robotic performance of object recognition tasks which are a precursor to other tasks, such as grasping and manipulation. Therefore, the ability to recognize the relevant objects, such as spoon, fork, cups and also pieces of the solid foods in the feeding environment is absolutely necessary.

Since the location of the cups, spoon and fork are predefined and almost fixed in the system, the vision system for this part, only checks their presence and assigns the number one for their presence inside the food tray. If any of these objects are missing from the tray, the system assigns zero for that specific object. The system of four cameras for users and four cameras for the food trays working together, have been presented in detail in the flowchart of the system in Chapter 4.

6.3 Image Acquisition and Preprocessing

6.3.1 Image Acquisition

The images from the food sections are acquired by a Sony DSC-V1 digital camera. The camera was not mounted on a frame; instead, images were obtained by the camera hand held in nearly static fixed positions. There are multiple objects (solid food pieces) to be recognized in the field of view. To facilitate determination of the objects from the background, colors that contrast greatly with the food items, such as blue and pink, were chosen for the food sections or plates. The surface of the plate or background is preferably a matt material that doesn't reflect the camera flash light or any other source of lights. The room's natural or overhead fluorescent lights are sufficient to provide enough illumination for the camera.

6.3.2 Image Histogram

A histogram of an image represents the relative frequency of the occurrence of various grey levels in the image, which gives its global description [82]. If the histogram is narrow, the image is poorly visible; and if it is wide, the overall contrast and visibility increases. The shape of the histogram reveals important contrast information, which can be used for image enhancement. Histogram equalization is a technique that entails adjusting the grey scale of the image so that the grey level histogram of the input image is mapped onto a uniform histogram, which is the goal of the output image.

6.3.3 Image Enhancement

Since the quality of the images to be processed may be poor, there may be a need to improve image quality in order to extract the required information. Increasing the dynamic range of chosen features in the image and undoing the degradation effects, caused by the imaging system or channel are essential parts of the procedure [83]. Preprocessing operations on the images make them more suitable for machine interpretation. Enhancement sharpens the image features, such as contrast, boundaries, edges, etc, but it does not increase the information content of the image data. The histogram equalization method is one example where the input grey levels are mapped so that the output grey level distribution is uniform. An important issue in image enhancement is quantifying the criterion for the enhancement.

6.4 Processing and Feature Extraction

6.4.1 Image Thresholding

The first algorithm that is run on the image is a histogram of the grey levels for separating out the background. Since the background is known to be homogenous, a peak observed in the histograms corresponds to background grey levels, which predominates the image. The picture is then thresholded at this level, driving all background pixels to zero. This gain in contrast between the background and figure is helpful in establishing gradients for the object's contours [83]. Grey level thresholding techniques are computationally inexpensive methods for partitioning a digital image into mutually exclusive and exhaustive regions [82]. The thresholding operation involves identification of a set of optimal thresholds, based on which the image is partitioned into several meaningful regions.

6.4.2 Edge Detection

After thresholding, an edge detection procedure is applied to images to find intensity changes in the image array. A magnitude threshold is established to filter out noise edges that are of small magnitude. This removes the edge elements related to physical effects in the image, which include shadows, occlusions and textures, as well as surface geometry. As a first approach, the edge detection technique was applied to images of cut up pieces of toasted bread, but it failed to recognize and extract features of some of the pieces in the image.

6.4.3 Segmentation

Segmentation involves partitioning an image into a set of homogeneous and meaningful regions, such that the pixels in each partitioned region posses an identical set of properties or attributes [82]. An image is thus defined by a set of regions that are connected and non-overlapping, so that each pixel in the image acquires a unique region label that indicates the region it belongs to. The set of objects of interest in an image, which are segmented, undergoes subsequent processing, such as object classification and scene description.

Segmentation algorithms are based on one of the two basic properties of grey-level values, *discontinuity* and *similarity* among the pixels. In the first algorithm, the image is partitioned based on sudden changes in grey level. The areas of interest within this category are the lines and edges in an image. Thus if the edge of an image can be detected and linked, then the region can be described by the edge contour that contains it. In the second algorithm, the connected sets of pixels, having more or less the same homogeneous intensity, form the regions. Thus the pixels inside the regions describe the region and the process of segmentation involves partitioning the entire scene in a finite number of regions.

The well established segmentation techniques are: 1) histogram-based thresholding, 2) region growing, 3) region splitting and merging, 4) clustering or classification, 5) graph theoretic approach, 6) rule-based or knowledge-driven approach. For the case of food images, the region growing and thresholding methods were applied to differentiate between pieces of touching or overlapping toast.

6.4.4 Filling the Gaps

Due to the discrete nature of convolutions, zero-crossings do not always form closed curves. Typically, small pixel gaps will appear, preventing a closed contour chain of 8-connected zero-crossings. A part of the coding is used to close these gaps and form closed contours of zero-crossings and fill inside the gaps.

6.4.5 Region Growing

Region growing refers to the procedure that groups pixels or subregions into larger regions. The analysis separates the image into regions bounded by closed contours and calculates measures for each region. The recursive growing operation on the image tries to grow these pixels' 4-connected neighbours until a border is found [83]. The important issues in the region growing are: 1) similarity, which denotes the minimum difference in the grey level observed between two spatially adjacent pixels or average grey level of a set of pixels, yielding different regions (if this difference is less than the similarity threshold value, the pixels belong to the same regions); and 2) area of the region where the minimum area threshold is associated with the smallest region size in pixels (in the segmented image, no region will be smaller than this threshold, which is defined by the user [82]).

6.4.6 Region Analysis

Each region is further analyzed for extracting the centroid, the area, the perimeter, or other useful and necessary information. The primary purpose of region analysis for images of solid food parts is to find the centroid of each piece inside the flat section of the food tray. This is the point where the robot inserts the fork. This becomes particularly important when only a few pieces of food remain inside the food section and the chances of picking up the food, without accurately detecting the centroid areas, drastically decreases. The adjacency relations, as an important part of the analysis, will be used in matching against the model database. They can be found by examining contour pixels that separate regions and by looking at the colors of their 8-connected neighbours.

6.4.7 Feature Extraction

A huge volume of information can be reduced by extraction of particular relevant features out of a scene. This not only improves the reliability of the processing but shortens processing time. Some of the most frequently used geometrical features are: area, perimeter, radius, moment of inertia or ratio between them [84]. The area measurement can be directly calculated by adding the number of square pixels that define an object in a binary image. The measured area varies according to the orientation of the object in the plane. The perimeter, however, cannot be found by counting the pixels of the contour, since the distance between the neighbouring pixels is 1 in the vertical and horizontal directions and $\sqrt{2}$ in diagonal directions. The perimeter is found by the weighted sum of the number of pixels of the contour, according to their relative position with respect to their neighbours.

6.5 Segmenting the Pieces of Solid Food

To develop the recognition and segmentation algorithm, it is not helpful to start by considering the worst, most complicated case in the image and then trying to extract information out of it. Simplifying the cases and making different, possible scenarios with similar objects inside the food sections, provides the opportunity to investigate different kinds of associated problems with those objects and view the problem from different vantage points. One typical kind of solid food, cut pieces of toasted bread, was chosen for testingn the algorithm and finding out the effect of each procedure on the original images. The images were processed as shown in Figure 6-1.

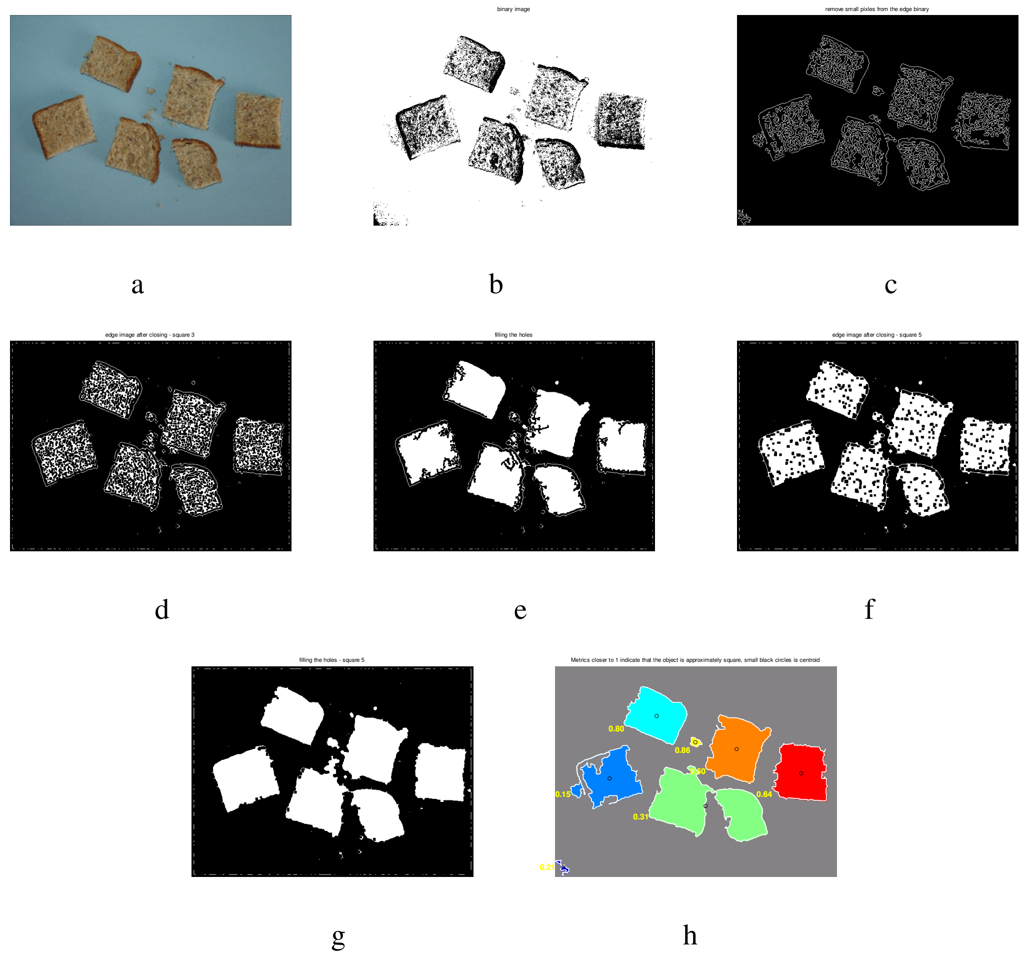
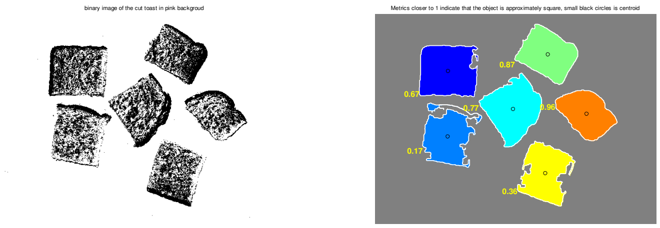


Figure 6-1: a) original image, b) binary image, c) removing small pixels from the edge detected image 3, d) image c after closing with square 3, e) filling gaps of image d, f) image 4 after closing with square 5, g) filling gaps of image 7, h) segmentation and centroid extraction.

This approach used the edge detected image (by log filter) for further processing such as closing and filling the gaps. Even though the pieces of toast were not touching or even very close to each other, the series of procedures failed to detect two of the pieces correctly. They led to detecting two adjacent pieces as one region and putting the centroid somewhere between the two bounded regions. However, further modifications, such as applying a canny filter instead of a log filter and removing more small pixels from the image, could solve the problem of finding correct centroids for this particular image as shown in Figure 6-2. However, bread crumbs in the images formed small bounded areas causing an overestimation in the number of closed boundaries; 10 parts were detected instead of 6. Applying a threshold could remove these small bounded areas. For instance, areas smaller than 500 or 700 pixels could be eliminated.

Figure 6-2: Correctly found centroids of image in Figure 6-1-1.



a b

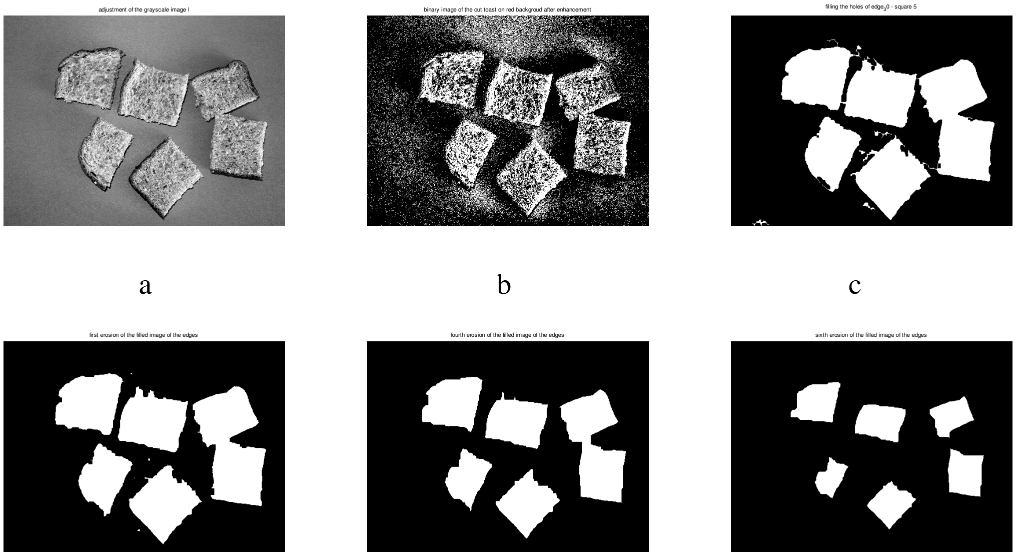
Figure 6-3: a) Binary image b) correctly found centroids.

a b

Figure 6-4: a) Original image b) Error in final segmentation.

a b

Figure 6-5: a) Original image, b) Error in final segmentation.



a b c

d e f

Figure 6-6: a) adjustment of the greyscale image, b) binary image after enhancement, c) filling the holes of the edge image (square 5), d) first erosion of the filled gaps of the edge, e) fourth erosion, f) sixth erosion.

Although some images, such as the one shown in Figure 6-3 work properly with this algorithm, it can be seen that it fails considerably in properly segmenting the pieces of toast and locating the centroids in others (see Figure 6-4 and Figure 6-5). The image enhancement functions *imadjust* and *adapthisteq* were applied to the image shown in Figure 6-6-1 to add contrast to the image and to equalize the histogram, respectively. The *graythresh* function computed a global threshold using

Otsu’s method to convert an intensity image to a binary image. A morphological flat structuring element of the type specified by a disk shape with radius 5 was created.

6.6 Touching/Overlapping Problem

In previous tests, the program was not able to handle touching or overlapping pieces of the toasted bread. Difficulties in finding a parameter or threshold that works for most of the touching or overlapping cases, required refinement of parameters used. Three pieces of cut toast of similar shape and size were randomly placed beside each other close enough to just touch each other but not to overlap.

The program was run with only small changes made for each input image. The change of parameters each time helped to determine the closest and best parameters that may be used for all similar cases. It is assumed that the nurse/caregiver will not put pieces of toast on top of each other or overlap them. To simplify the recognition of each piece of toast, it has been assumed that the corner of the each piece touches the side of another one.

The colors of the food image background (food section) are chosen from colors that would typically contrast with food items such as blue. Another simplification was to place the toast pieces on blue pieces of paper/cardboard instead of the shiny plates, which readily, reflect environmental light. The simplification of the problem at this time is just to be able to focus on the segmentation of each piece, even if they are touching each other.

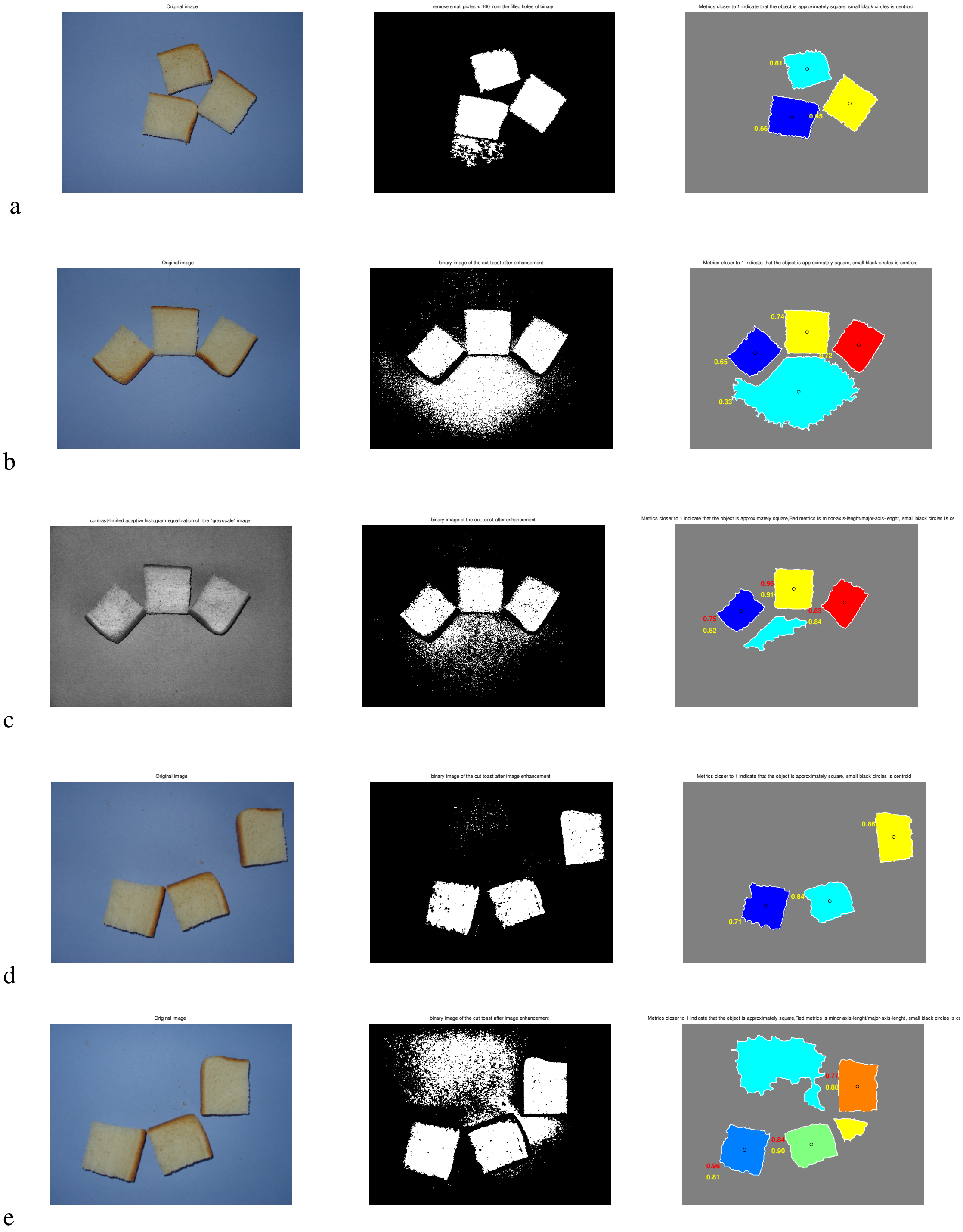


Figure 6-7: Results for some selected possible arrangements (6-7a to 6-7e) of three pieces of touching cut toast.

6.7 Discussion of Results

The algorithm identifies each piece of toasted bread inside the food section. Since it ignores segments smaller than a specific area (number of pixels) it will identify only the blobs of interest. The information related to the location and orientation of each blob, such as its area, and its closeness to a specific shape (such as square, or triangle) is identified. This information is then used to determine which possible segments correspond to the piece of toasted bread that should be picked up by the fork. The centre of each blob and its two dimensional coordinates will be available for use by planning and action agents. These points demarcate where the fork is to be inserted into each piece of toasted bread. The sensing agent determines the initial locations of the objects inside the food tray during the eating process, such as cups, fork and spoon and pieces of solid food.

Since the pieces of toast or any other solid food inside the food section can come in a variety of colors, it would be difficult to teach the system to pick up specific pre-learned colors. However we assume that the solid foods can be cut into smaller pieces and simple shapes, such as squares (or triangles); therefore, the blobs that closely resemble a specified shape can be selected as the regions of interest. To make this happen, a metric for any segment to be square (or triangle) is defined. The metrics which are closer to 1 are more similar to squares. Applying a filter can have the advantage of getting rid of blobs that have very irregular shapes and are not similar to the square or the specific shape being looked for.

Similar results have been observed for most of the other cases. It seems that the illumination of the image, as shown in Figure 6-7(b), plays an important role in the image. Enhancement of the image may have an affect on the final binary image. It has been attempted, through several trials, to determine which features of the program (illumination, enhancement technique, filling or closing method) have the greatest effects on the results. This type of investigation helped to understand the parameters or thresholds which should be used in the program, as well as, the steps that should be considered more carefully. Removing the adjustment step from the algorithm, as shown in Figure 6-7(c), made the area of the non-object regions much smaller. The falsely detected regions, shown in Figure 6-7(e), can be removed by either applying a higher threshold, more erosion, or defining a parameter such as closeness to the square, thus excluding them from the group of centroid locations, which are the regions intended to be specified. That is, the small circles, representing the centroid of the pieces of toast, are not placed over the false regions.

The light direction, its quality, and intensity have a significant influence on the final image processing results. The shadows of 3D pieces of cut toast in the image are a kind of distortion caused by the lighting system, which conceals information relevant to the recognition of each piece, such as their edges. False information (noise), dimensional distortion, and concealing of information are some of the negative effects on image processing. The shadows that the pieces of cut toast, project on the background plate lead to a shift in the limits between the object and the background in the image, thus changing the observed geometric magnitude. It is obvious from the above results that this distortion has caused difficulties in recognition and segmentation of each piece of cut toast, and contributes to errors in computations of the centroid location of each piece.

The information from the image processing section such as the central point of the solid food parts would be transferred to the ADAMS model which has also been integrated with MATLAB. However this part of the global project is beyond the scope of this thesis and will be carried out as the next phase of the project in the future.

Chapter 7

Closure

A preliminary study on an intelligent multiple-user feeding robot was presented. Various feeding devices, including those available in the market and those still in various stages of development, were introduced and discussed. Different user interfaces with the potential to be used in the proposed feeding system, as well as their advantages and disadvantages, have also been explained. The idea for a multiple-user feeding device was generated during observation sessions in a nursing home, where continued examination of the elderly and their caregivers during meal time has provided ample support, both in terms of motivation and supply of critical information, for the development of such a device.

7.1 Observations

The design concept and criteria for the feeding device were based on general and special requirements of the elderly and specific limitations in their eating capabilities. The behaviour of the elderly while eating, the challenges of both senior people and the caregivers in the dining area during the meal time were closely investigated in both the regular care unit and the special care unit of the nursing home. The observations helped to determine the characteristics and needs of the population who can benefit from such a feeding device, and they also clarified the scope of the design. This information provided a guideline for decisions regarding the type of robot and its configuration, and also a user interface for simultaneous feeding of multiple users sitting at a four-seat table.

The residents in special care unit with Alzheimer's disease could not logically connect hunger to food or to feeding. They needed to be reminded about the next task after finishing each step, since they were forgetting the necessary steps for feeding themselves, even chewing or swallowing. Different and unpredictable daily behaviour (related to different foods or a new device) and getting easily confused with some options to choose from, were important factors that had to be considered in making a comfortable and stress-free feeding for this population. The ways the machine and user interact with one another are extremely important; an appropriate user interface helps to address users' cognitive disabilities. A good comprehension by the users of the environment and the required tasks for the procedures of eating will only be achieved by an appropriate user interface.

The residents in the regular care unit mostly suffered from upper-limb dysfunctions, which made it difficult for them to eat by themselves. In addition, having no control of their head and neck, severe head tremor, inability to open their mouths to be fed, and severe swallowing or chewing problems, were typical physical difficulties that made 40% of the population dependent on caregivers. Among the rest of the 60%, more than 40% had problems such as hand tremor, lack of strength in holding the utensil, and severe joint pain in arm, wrist, or finger. They had difficulties in manipulating the spoon or fork and directing it toward the mouth. The lipped plates with dividers helped about 11.7% of the elderly in better scooping. For each user, 3- 4 different kinds of food and dessert and 2- 4 cups were considered. Many of the foods (about 31.7%) were pureed for those with chewing or digestion problems and many of them were cut into pieces for those with lack of strength in their hands. Some were using gel foods because of chewing and swallowing difficulties.

According to the observations and the caregivers' opinion at the present time, having a feeding device would be beneficial in the environment where many elderly people dine together at standard four-seat tables. The meal time was very challenging for both residents and caregivers since the time allocated for eating and the numbers of caregivers were limited. Indeed, one nurse could respond to a maximum of two diners at the same time and could only manage to respond to the needs of all diners with the assistance of the limited number of staff members available. The target users in the proposed design have been considered as either female or male adults including elderly people (no children at the present time) in senior houses, nursing homes or hospitals (where they receive special care) who have weak muscles or joints in their hands or arms. They may suffer from muscle stiffness and cannot grab or handle a spoon or fork easily or have significant tremor in their hands while eating. The users should have control of neck and head muscles and; be cognitively aware of the environment; be able to see and read labels, hear sounds, word, tones and characters and; be able to talk in such a way that the words and characters are recognizable by others.

Form the safety point of view, the users should have sufficient control of their neck and head, enough to keep it in an upright position or at an angle that would be safe in the nurse's opinion. This reduces the potential of choking while swallowing. The end effector does not reach the user's mouth, but should force the user to reach slightly for the spoon. The force applied by the robot must be within a range that does not hurt the users. The robot's end effector should avoid hurting the user by stopping at the closest predefined distance to the user's mouth. This will be more important when the robot is using a fork which has pointed tines. Also, the spoon or fork should not retract when it is inside and touching the user's mouth. If the location of the user's mouth is beyond the workspace of the robot (when the user is further than the predefined allowable distance), the robot should notify the user to sit closer to the table's edge. Continuous head tremor, not only makes the user's mouth tracking very difficult, but it may cause the force sensor at the end of the end effector to be unreliable when touching the user's mouth. Incorrect data may lead to an applied force to the user that causes injury.

7.2 Multiple-user feeding system

The idea of having a machine that is capable of simultaneously feeding multiple users in such places as nursing homes seemed advantageous, in the first place, for many reasons: a) dramatic reduction of the number and consequent costs of nurses or caregivers by assignment of one feeding device to a maximum of four people in such institutions; and b) allotment of the time-gap required for one person to chew and swallow, to feed another person sitting at the same table (longer gap for elderly individuals with slower paces of eating).

This idea has moved beyond conceptualization to virtual design of the whole system; including the food tray, appropriate selection of the robot, and the careful arrangement of the robot and food trays on a four-seat dining table. It was assumed that issues related to food (e.g. cutting solid foods into pieces and putting them in the right place in the food tray), the user (making the users sit in an upright safe position for eating) and the environment (having sufficient light) would be taken care of or checked by the care or service providers in the dining area.

7.3 Design

In the design, it was attempted to fit four cups and four food sections in an arc shape tray because this way the robot could be located in the center of the arc to make it easier for the robot to feed multiple persons. Scooping of the food would be much easier compared to using a square or round plate with three or four compartments. The food trays could also be put beside each other with one robot at the center for feeding four users Based on calculations of the minimum amount of food and liquid required by users, the positions of food sections, cups, spoons and forks, were determined in order to fit all utensils and food sections.

The robot was chosen such that it can be small enough to fit on a four-seat table with a standard height of 72-74 cm (with a diameter of almost 60 cm). A serial manipulator was selected so it can rotate almost 350-360 degree at the base to provide large workspace and respond to all users. A payload of 2-3 kg was considered sufficient for picking up the weight of the food and utensil or drinking cups. The rotation angles of joints and the length of link were supposed to be able to provide the maximum reach between 800- 836 mm and reach to predefined locations on the dining table to pick up a spoon, fork or any of the cups for each user. The height of the robot's waist was chosen to be lower than the user's eye level when user sits behind the table (it might not be too obtrusive). A non-redundant robot with six DOF was selected, to freely position and orient the objects in a Cartesian workspace.

The minimum or desired system requirements such as type of robot joints, length of links, maximum weight, maximum payload, maximum and minimum reach, and workspace of the robot were specified based on the determined user's characteristics and also the feeding environment. Some of the data that impacted on this decision were: the desired model configuration, strength and dimensions of a standard four-seat table to hold the robot on top, the weight of the utensils plus food and cups filled with drink, the distance between the outer edge of the food tray with the edge of the table, the anthropometric data of a typical adult in seated position such as the height of the mouth and eye, and the distance of the head/mouth from the table. The selected robot was a CRS-A465, with 31 kg weight and maximum 2 kg payload on the end effector. The waist of the robot could rotate from -175 to +175 degrees. The maximum reach of the robot was 711 mm without the end effector and 864 mm with a standard end effector (not considering the length of the spoon/fork). The three joint axis of the 3-DOF wrist intersected at one point, which had the advantage of providing the closed-form solution for the kinematic and dynamic analyses.

The whole feeding system, including the robot, food trays, and table, was simulated in ADAMS to help in three-dimensional visualization of the robot and its environment. The rationale for the application of a vision system as an interface, along with its arrangement and settings with respect to the food trays and the users were presented. The method of interaction between cameras, users, and robot manipulators was explained in detail in the robot and vision related task section, and it was schematically shown in flowcharts of the system. It was designed that the presence of the users behind the table and the mouth locations would be checked and tracked by four cameras, one beside each user. In addition, for recognizing the locations of the central parts of solid food parts and checking the existence of utensils or food parts inside the tray, four other cameras were planned to be used, one for each food tray. The interaction of multiple users, cameras and objects, requires considerable management of received commands from different users and captured images from different cameras.

7.4 Vision system

The proposed vision system, would acquire many images of the food trays and users' faces. The food tray images would be used for segmenting and recognizing each piece of solid food inside the flat plate and finding the centers of each piece (the fork would be inserted into this point to pick up the piece); as well as checking the presence of the cups ad utensils in their places (it was assumed that their location and shapes are already fixed and known).

The feeding robot task was divided into two parts. The first part was a pick-and-place type operation in a constrained environment, where only partial knowledge of the relevant objects to be manipulated would be assumed to be known. The spoon, the fork, and the cups were objects to be recognized. This meant that the robot would know the vicinity of its approach and the exact location and orientation of the objects would not be known. The second part consisted of an active system which used sensory or visual feedback to understand the environment. Some of the objects to be recognized were different pieces of solid foods that were not necessarily placed in the same position and orientation in the food tray sections.

In order to achieve acceptable accuracy levels of food recognition, specifically the centroid locations in small pieces of toast, an image processing algorithm was developed, which also aided in checking the location of the cups and utensils.

Future research can address the following issues as force control and user safety, the addition of compliant devices to reduce the risk of injury to users, expanding or optimizing the image processing algorithm for other types of foods, seamless integration of the robotic and vision systems, addition of alternative user interfaces in response to the vast range of user needs, production of a prototype of the system, testing and evaluating the prototype on real users.

Appendix A

Anthropometric Data[3] of an Adult Person

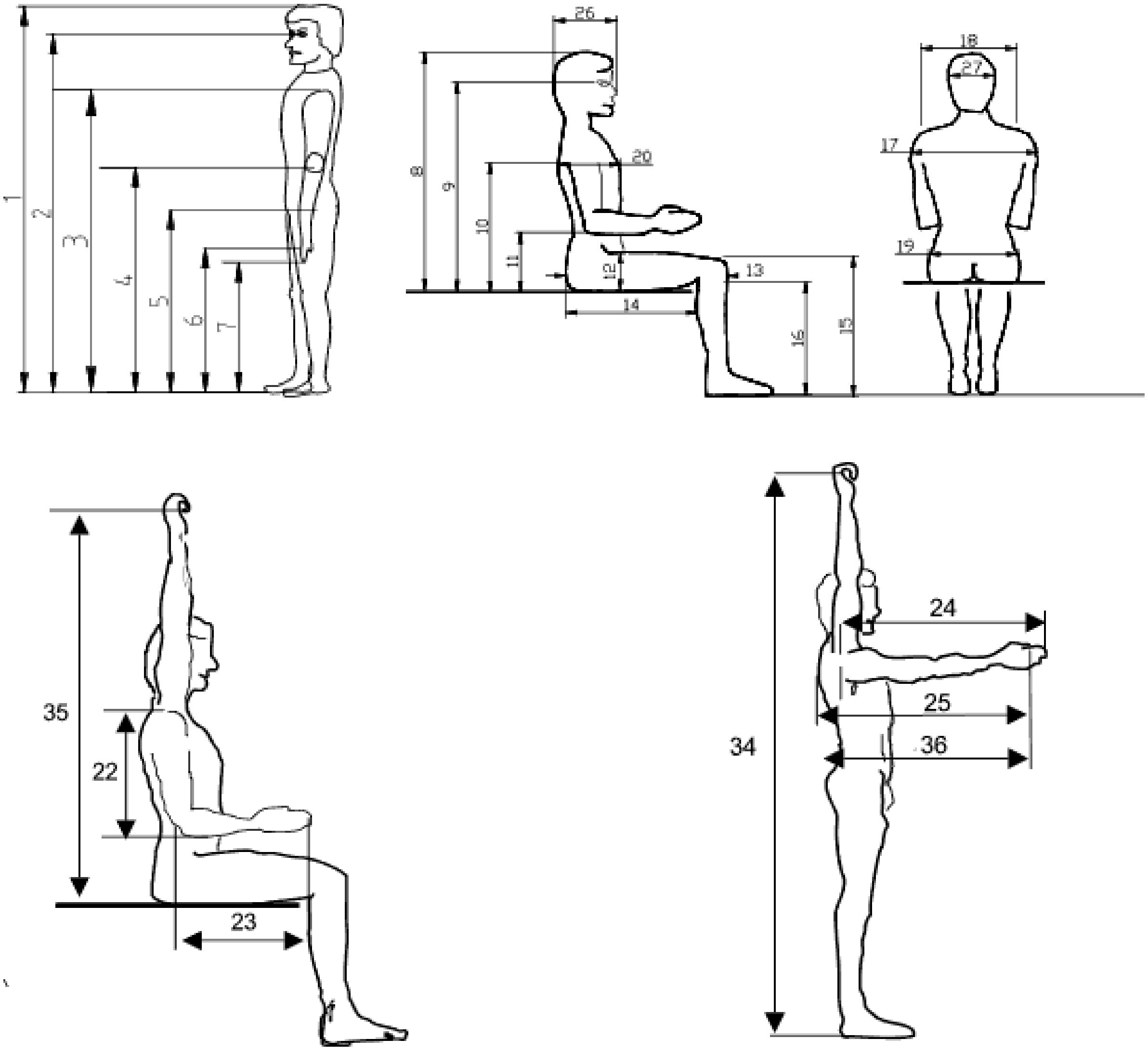


Figure: Anthropometric data of an adult person [87].

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[3] These are data related to dimensions of living human body parts mostly in static positions.

Table A.1. Anthropometric data of Men and Women[4] [87], all dimensions are in [mm].

Dimension s	Man (Percentiles)		Women (Percentiles)	
	5%	95%	5%	95%
1- Height	1625	1855	1505	1710
2-Eye	1515	1745	1405	1610
3-Shoulder Height	1315	1535	1215	1405
4-Elbow Height	1005	1180	930	1085
5-Hip Height	840	1000	740	885
6-Knuckle Height	690	825	660	780
7-Fingertip Height	590	720	560	685
8-Sitting Height	850	965	795	910
9-Sitting Eye Height	735	845	685	795
10-Sitting Shoulder	540	645	505	610
11-Sitting Elbow Height	195	295	185	280
12-Thigh Thickness	135	185	125	180
13-Buttock-Knee Length	540	645	520	620
14-Buttock-popliteal length	440	550	435	530
15-Knee Height	490	595	455	540
16-Popliteal Height	395	490	355	445
17-Shoulder Breadth	420	510	355	435
18-Shoulder Breadth	365	430	325	385
19-Hip Breadth	310	405	310	435
20-Chest Depth	215	285	210	295
Dimension s	Man (Percentiles)		Women (Percentiles)	

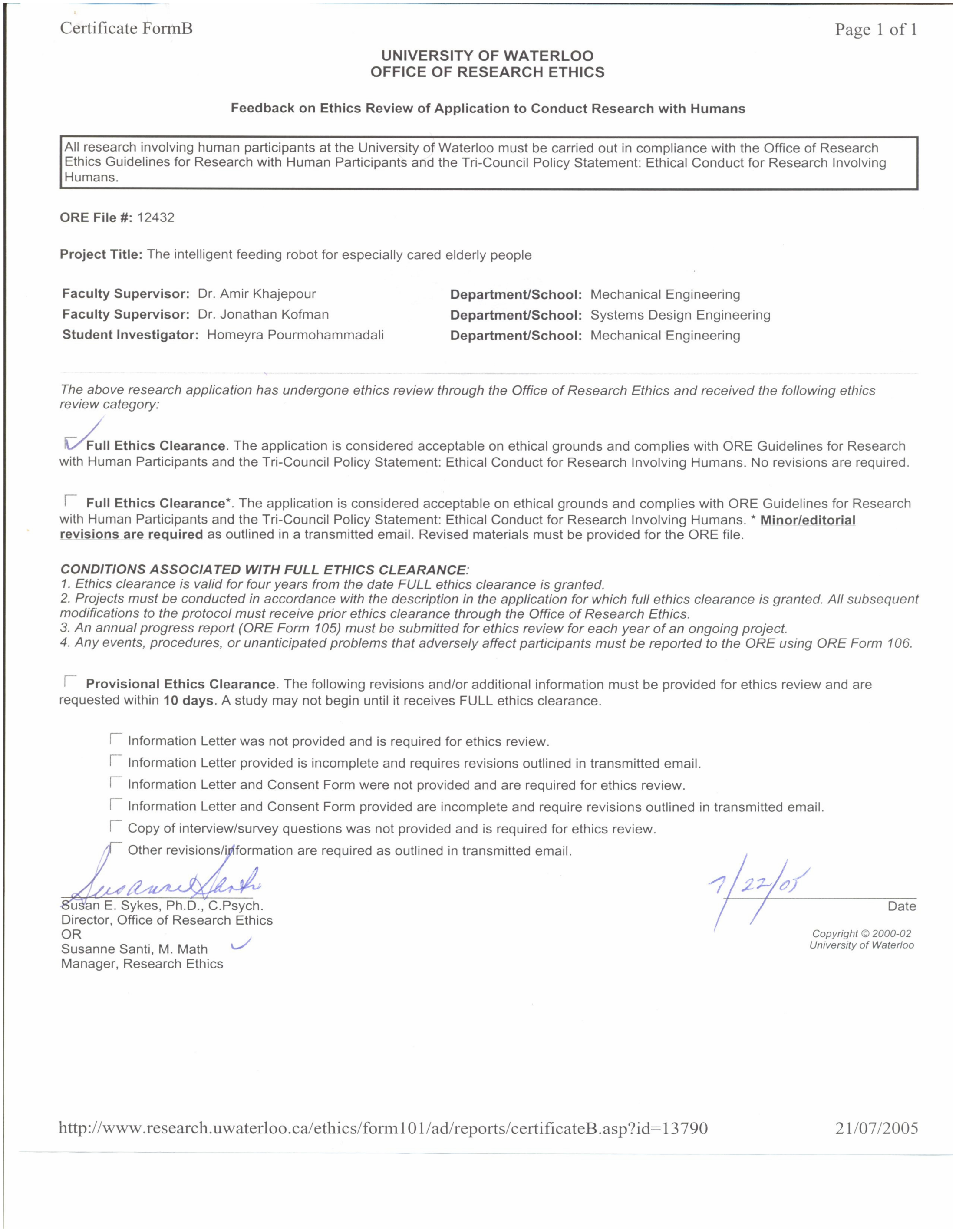
---

[4] The table relates to British person and the size range shows the mid 90% range of people sizes in the UK.

	5%	95%	5%	95%
21-Abdominal Depth	220	325	205	305
22-Shoulder-Elbow Length	330	395	300	360
23-Elbow Fingertip Length	440	510	400	460
24-Upper Limb Length	720	840	655	760
25-Shoulder Grip Length	610	715	555	650
26-Head Length	180	205	165	190
27-Head Breadth	145	165	135	150
28-Hand Length	175	205	160	190
29-Hand Breadth	80	95	70	85
30-Foot Length	240	285	215	255
31-Foot Breadth	85	110	80	100
32-Span	1655	1925	1490	1725
33-Elbow Span	865	1020	780	920
34-Vertical Reach	1925	2190	1790	2020
35-Vertical Reach (sit)	1145	1340	1060	1235
35-Forward Grip Reach	720	835	650	755

Appendix B

Research Ethics Review Feedbacks



Certificate FormB

Page 1 of 1

UNIVERSITY OF WATERLOO
OFFICE OF RESEARCH ETHICS

Feedback on Ethics Review of Application to Conduct Research with Humans

All research involving human participants at the University of Waterloo must be carried out in compliance with the Office of Research Ethics Guidelines for Research with Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans.

ORE File #: 12432

Project Title: The intelligent feeding robot for especially cared elderly people

Faculty Supervisor:	Dr. Amir Khajepour	**Department/School:**	Mechanical Engineering
Faculty Supervisor:	Dr. Jonathan Kofman	**Department/School:**	Systems Design Engineering
Student Investigator:	Homeyra Pourmohammadali	**Department/School:**	Mechanical Engineering

The above research application has undergone ethics review through the Office of Research Ethics and received the following ethics review category:

☑ **Full Ethics Clearance**. The application is considered acceptable on ethical grounds and complies with ORE Guidelines for Research with Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans. No revisions are required.

☐ **Full Ethics Clearance***. The application is considered acceptable on ethical grounds and complies with ORE Guidelines for Research with Human Participants and the Tri-Council Policy Statement: Ethical Conduct for Research Involving Humans. * **Minor/editorial revisions are required** as outlined in a transmitted email. Revised materials must be provided for the ORE file.

CONDITIONS ASSOCIATED WITH FULL ETHICS CLEARANCE:
1. Ethics clearance is valid for four years from the date FULL ethics clearance is granted.
2. Projects must be conducted in accordance with the description in the application for which full ethics clearance is granted. All subsequent modifications to the protocol must receive prior ethics clearance through the Office of Research Ethics.
3. An annual progress report (ORE Form 105) must be submitted for ethics review for each year of an ongoing project.
4. Any events, procedures, or unanticipated problems that adversely affect participants must be reported to the ORE using ORE Form 106.

☐ **Provisional Ethics Clearance**. The following revisions and/or additional information must be provided for ethics review and are requested within **10 days**. A study may not begin until it receives FULL ethics clearance.

- ☐ Information Letter was not provided and is required for ethics review.
- ☐ Information Letter provided is incomplete and requires revisions outlined in transmitted email.
- ☐ Information Letter and Consent Form were not provided and are required for ethics review.
- ☐ Information Letter and Consent Form provided are incomplete and require revisions outlined in transmitted email.
- ☐ Copy of interview/survey questions was not provided and is required for ethics review.
- ☐ Other revisions/information are required as outlined in transmitted email.

Susanne Santi

Susan E. Sykes, Ph.D., C.Psych.
Director, Office of Research Ethics
OR
Susanne Santi, M. Math
Manager, Research Ethics

7/22/05
Date

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http://www.research.uwaterloo.ca/ethics/form101/ad/reports/certificateB.asp?id=13790 21/07/2005

Appendix C

CRS –A465 Characteristics and Dimensions

Table C-1: Joint specifications for A465 robotic arm [A465 User's Guide].

Axis	Joint 1	Joint 2	Joint 3	Joint 4	Joint 5	Joint 6
Range of Motion	± 175°	± 90°	± 110°	± 180°	± 105°	± 180°

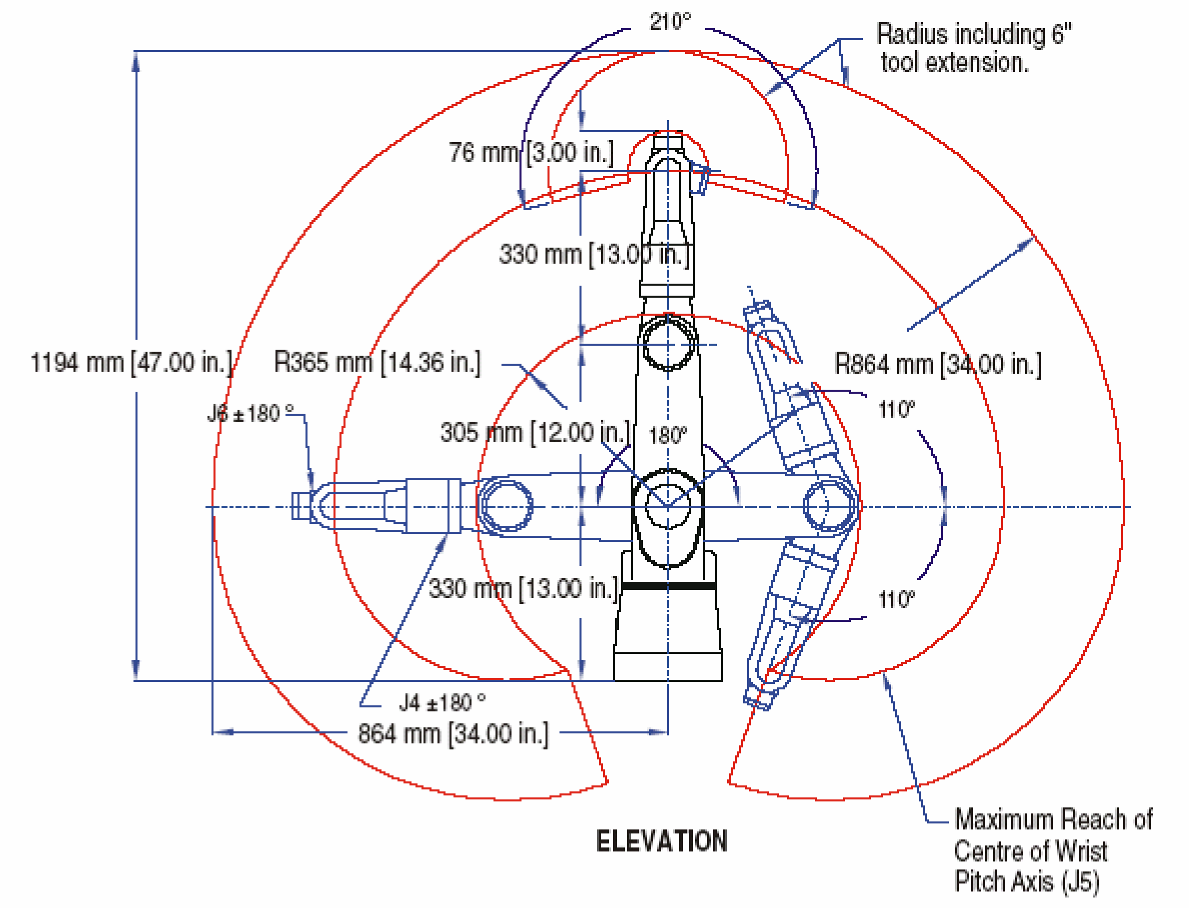

Figure C.1. Workspace[5] and dimensions of CRS A465 robot [A465 User's Guide].

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[5] Workspace is the volume swept by all robot parts and the end effector and the workpiece.

Appendix D

Kinematic and Dynamic of the Manipulators

D.1. Kinematic

The Denavit-Hartenberg (DH) [88]technique proposes a matrix method that systematically assigns coordinate systems to each link of an articulated chain. The axis of revolute joint i is aligned with z_{i-1}. The x_{i-1} axis is directed along the normal from z_{i-1} to z_i and for intersecting axes is parallel to $z_{i-1} \times z_i$. The link and joint parameters can be summarized as:

θ_i is the joint angle which is the angle between the x_{i-1} and x_i axes about the z_{i-1} axis.

α_i is the twist angle which is the angle from z_{i-1} axis to the z_i axis about the x_i axis.

a_i is the link length that is the distance between the z_{i-1} and z_i axis along the x_i axis.

d_i is the link offset that is the distance from the $(i-1)^{\text{th}}$ frame to the x_i axis along the z_{i-1} axis.

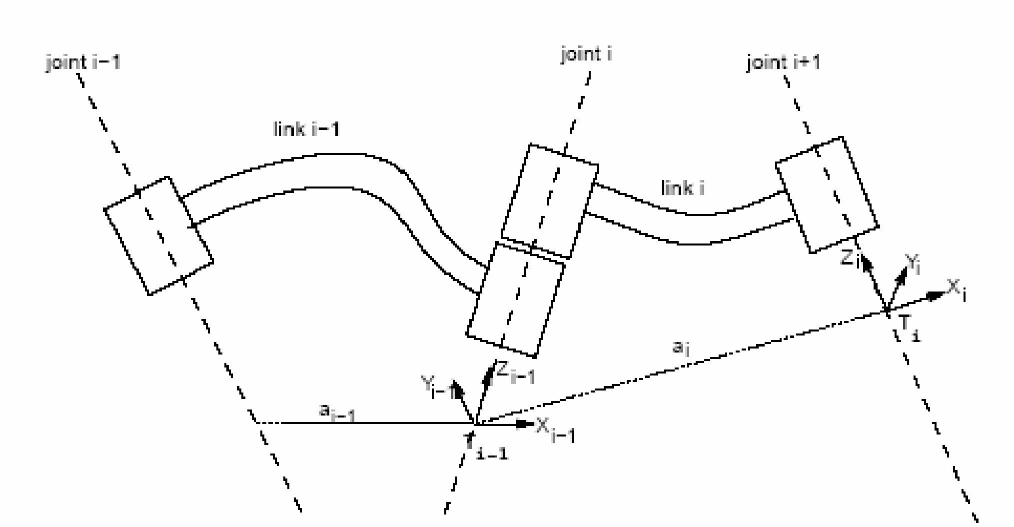

Figure D.1. Standard form [88].

For the revolute axis θ_i is the joint variable and d_i is constant. The 4×4 homogenous transformation matrix for each revolute joint, which represent each link's coordinate frame with respect to the previous link's coordinate system, is:

$$ {}^{i-1}A_i(\theta_i) = \begin{bmatrix} \cos\theta_i & -\sin\theta_i\cos\alpha_i & \sin\theta_i\sin\alpha_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\theta_i\cos\alpha_i & -\cos\theta_i\sin\alpha_i & a_i\sin\theta_i \\ 0 & \sin\alpha_i & \cos\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_i & -s_i\lambda_i & s_i\mu_i & a_ic_i \\ s_i & c_i\lambda_i & -c_i\mu_i & a_is_i \\ 0 & \mu_i & \lambda_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} $$

(D-1)

where: $\lambda_i = \cos\alpha_i$, $\mu_i = \sin\alpha_i$, $c_i = \cos\theta_i$, and $s_i = \sin\theta_i$. The values of α_i s, a_i s and d_i s are found from the defined DH table for the selected robotic system. The problem of inverse kinematics corresponds to computing the joint angles θ_1 to θ_6 such that:

$$ T_1.T_2.T_3.T_4.T_5.T_6 = T_{end} \qquad \text{(D-2)} $$

D.1.1. Transformation Matrices of CRS- A465

Each link is represented by the line along its joint axis and the common normal to the next joint axis. The links of the 6R manipulators are numbered from zero to six in such a way that the base link is zero and the outermost link or hand is six. A coordinate system is attached to each link for describing the relative arrangements among the various links. The coordinate system, attached to the *i*th link is numbered *i*. Based on these definitions:

$$ \begin{aligned} &\mathrm{L} = [0 \quad \ell_b \quad \ell_c \quad 0 \quad 0 \quad 0\,] \\ &\alpha = [\,\alpha_1 \quad \alpha_2 \quad \alpha_3 \quad \alpha_4 \quad \alpha_5 \quad \alpha_6\,] \\ &\mathrm{d} = [0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0\,] \\ &\theta = [\theta_1 \quad \theta_2 \quad \theta_3 \quad \theta_4 \quad \theta_5 \quad \theta_6\,] \\ &\ell_b = 0.35\,m,\ \ \ell_c = 0.33\,m \end{aligned} \qquad \text{(D-3)} $$

$$ \begin{aligned} &\alpha_1 = 90^\circ, \quad \cos\alpha_1 = 0,\ \sin\alpha_1 = 1 \qquad &&\alpha_4 = 90^\circ, \quad \cos\alpha_4 = 0,\ \sin\alpha_4 = 1 \\ &\alpha_2 = 0^\circ, \quad \cos\alpha_2 = 1,\ \sin\alpha_2 = 0 &&\alpha_5 = -90^\circ, \quad \cos\alpha_5 = 0,\ \sin\alpha_5 = -1 \\ &\alpha_3 = 0^\circ, \quad \cos\alpha_3 = 1,\ \sin\alpha_3 = 0 &&\alpha_6 = 0^\circ, \quad \cos\alpha_6 = 1,\ \sin\alpha_6 = 0 \end{aligned} \qquad \text{(D-4)} $$

and the transformation matrices are:

$$T_{01} = \begin{bmatrix} c_1 & 0 & s_1 & 0 \\ s_1 & 0 & -c_1 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{(D-5)}$$

$$T_{02} = \begin{bmatrix} c_1 c_2 & -c_1 s_2 & s_1 & l_b c_1 c_2 \\ s_1 c_2 & -s_1 s_2 & -c_1 & l_b s_1 c_2 \\ s_2 & c_2 & 0 & s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{(D-6)}$$

$$T_{03} = \begin{bmatrix} c_1 c_{23} & -c_1 s_{23} & s_1 & c_1 (l_c c_{23} + l_b c_2) \\ s_1 c_{23} & -s_1 s_{23} & -c_1 & s_1 (l_c c_{23} + l_b c_2) \\ s_{23} & c_{23} & 0 & l_c s_{23} + l_b s_2 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{(D-7)}$$

$$T_{04} = \begin{bmatrix} c_1 c_{234} & s_1 & c_1 s_{234} & c_1 (l_c c_{23} + l_b c_2) \\ s_1 c_{234} & -c_1 & s_1 (c_4 s_{23} - s_4 c_{23}) & s_1 (l_c c_{23} + l_b c_2) \\ c_4 s_{23} - s_4 c_{23} & 0 & -c_{234} & l_c (s_{23} + l_b s_2) \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{(D-8)}$$

$$T_{05} = \begin{bmatrix} c_1 c_5 c_{234} + s_1 s_5 & -c_1 s_{234} & c_1 s_5 c_{234} + s_1 c_5 & c_1 (l_c c_{23} + l_b c_2) \\ s_1 c_5 c_{234} - c_1 s_5 & -s_1 s_{234} & -s_1 s_5 c_{234} + c_1 c_5 & s_1 (l_c c_{23} + l_b c_2) \\ c_5 s_{234} & c_{234} & -s_5 s_{234} & l_c (s_{23} + l_b s_2) \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \text{(D-9)}$$

$$T_{06} = \begin{bmatrix} c_1 (c_6 c_5 c_{234} - s_6 s_{234}) + c_6 s_1 s_5 & -s_6 (c_1 c_5 c_{234} + s_1 s_5) - c_1 c_6 s_{234} & -c_1 s_5 c_{234} + s_1 c_5 & c_1 (l_c c_{23} + l_b c_2) \\ c_6 (s_1 c_5 c_{234} - c_1 s_5) - s_1 s_6 s_{234} & -s_1 (s_6 c_5 c_{234} + c_6 s_{234}) + s_6 c_1 s_5 & -s_1 s_5 c_{234} - c_1 c_5 & s_1 (l_c c_{23} + l_b c_2) \\ c_5 c_6 s_{234} + s_6 c_{234} & -c_5 s_6 s_{234} + c_6 c_{234} & -s_5 s_{234} & l_c (s_{23} + l_b s_2) \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

(D-10)

D.2. Dynamics

The dynamic model of the robot consist of an ordinary differential equation where the variable corresponds to the vector of positions and velocities, which may be in joint coordinates θ and $\dot{\theta}$ or in operational coordinates x and $\dot{x}$ [30]. The Lagrangian of $L(\theta,\dot{\theta})$ of a robot manipulator of n DOF and the Lagrange equations of motion for the robot manipulator are:

$$L(\theta,\dot{\theta}) = K(\theta,\dot{\theta}) - U(\theta),\ \frac{d}{dt}[\frac{\partial L(\theta,\dot{\theta})}{\partial \dot{\theta}_i}] - \frac{\partial L(\theta,\dot{\theta})}{\partial \theta_i} = \tau_i \qquad \text{(D-11)}$$

where K is the kinetic energy of the system and U is the total potential energy of the system, τ_i corresponds to the external forces and torques (delivered by the actuators) at each joint as well as to other (non-conservative) forces. In the class of non-conservative force, we include those due to friction, the resistance to the motion of the solid in a fluid and in general all those that depends on time and velocity and not only on position. Considering the kinetic energy function $K(\theta,\dot{\theta})$ as:

$$K(\theta,\dot{\theta}) = \frac{1}{2}\dot{\theta}^T M(\theta)\dot{\theta} \qquad \text{(D-12)}$$

where $M(\theta)$ is a symmetric and positive definite matrix of dimension 6×6 referred to as the inertia matrix, the dynamic equation in compact form would be:

$$M(\theta)\ddot{\theta} + C(\theta,\dot{\theta}) + g(\theta) = \tau \qquad \text{(D-13)}$$

where

$$C(\theta,\dot{\theta})\dot{\theta} = \dot{M}(\theta)\dot{\theta} - \frac{1}{2}\frac{\partial}{\partial\theta}[\dot{\theta}^T M(\theta)\dot{\theta}],\ g(\theta) = \frac{\partial U(\theta)}{\partial\theta} \qquad \text{(D-14)}$$

Equation (a) is the dynamic equation for robots of n DOF. Notice that (a) is a nonlinear vectorial differential equation of the state $[\theta^T\ \dot{\theta}^T]^T$. The $C(\theta,\dot{\theta})\dot{\theta}$ is the vector of dimension n called the vector of centrifugal and Coriolis forces, $g(\theta)$ is a vector of dimension n of gravitational forces or torques and τ is a vector of dimension n called the vector of external forces, which in general corresponds to torques and forces applied by the actuators at the joints.

Each element of $M(\theta)\ddot{\theta}$, $C(\theta,\dot{\theta})$ and $g(\theta)$ is, in general, a relatively complex expression of the positions and velocities of all the joints, that is, of θ and $\dot{\theta}$. The elements of $M(\theta)\ddot{\theta}$, $C(\theta,\dot{\theta})$ and $g(\theta)$ depend on the geometry of the robot. The inertia matrix is positive definite and its inverse exists. This is what allows us to express the dynamic model of any robot of n DOF in terms of the state vector $[\theta^T \dot{\theta}^T]^T$, that is:

$$\frac{d}{dt}\begin{bmatrix}\theta \\ \dot{\theta}\end{bmatrix} = \begin{bmatrix}\dot{\theta} \\ M(\theta)^{-1}[\tau(t) - M(\theta)\ddot{\theta} + C(\theta,\dot{\theta}) + g(\theta)]\end{bmatrix} \qquad \text{(D-15)}$$

Appendix E

Model of 6-DOF Robot in DynaFlexPro-Maple

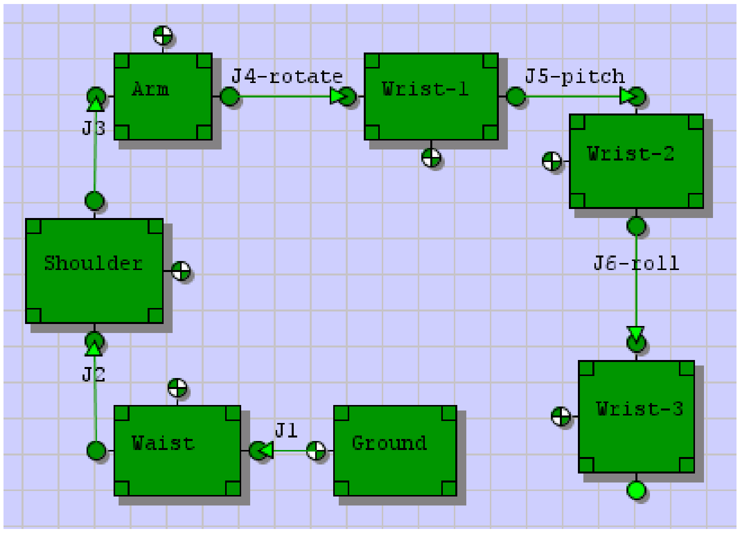

Figure E-1: Dynamic model of 6-DOF robot in DynaFlexPro Model Builder in Maple.

DynaFlexPro Input Model Generated by Model Builder

```
# DynaFlexPro Input Model
# Generated by Model Builder V1.0 Build 30
# Model name: A465
# -============== Global Model Parameters ==============-
use DynaFlexPro[mConstants] in
rMData["GroundNode"][DOM_MT] := "mGND":
rMData["GroundNode"][DOM_MR] := "mGND":
rMData["SysConsts"] := ["GravVec" = <0,0,-G>]:
# -============== Node Map ==============-
# Node 1: mGND
# Node 4: COM_2 on Shoulder
# Node 5: B2 on Shoulder
# Node 6: C2 on Shoulder
# Node 7: COM_3 on Arm
# Node 8: D3 on Arm
# Node 9: C3 on Arm
```

```
# Node 10: COM_4 on Wrist-1
# Node 11: D4 on Wrist-1
# Node 12: E4 on Wrist-1
# Node 13: COM_1 on Waist
# Node 14: A1 on Waist
# Node 15: B1 on Waist
# Node 16: COM_5 on Wrist-2
# Node 17: E5 on Wrist-2
# Node 18: F5 on Wrist-2
# Node 19: COM_6 on Wrist-3
# Node 20: F6 on Wrist-3
# Node 21: P on Wrist-3
# -============== Components ==============-
# Rigid Body "Shoulder": ,
rMData["Shoulder"] :=
        "SubIdent", "mRigidBody",
        "Description", "Rigid Body",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 1]],
        "NodeMap", [[DOM_MT, "mGND", "COM_2"], [DOM_MR, "mGND", "COM_2"]],
        "Params", ["Mass" = m2,
                "Inertia" =        [[Jxx_2,0,0],
                            [0,Jyy_2,0],
                            [0,0,Jzz_2]],
                "TranVars" = [x_2, y_2, z_2],
                "RotVars" = [zeta_2, eta_2, xi_2], "RotType" = "EA123",
                "AngVelVars" = [wx_2, wy_2, wz_2], "AngVelType" = "End"]:
# Mech Frame 5 (B2)
rMData["B2"] := "SubIdent", "mRigidBodyFrame",
        "Description", "B2",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "COM_2", "B2"], [DOM_MR, "mGND", "COM_2", "B2"]],
        "Params", ["TranConsts" = <-Lc2,0,0>,
                "RotConsts" = [0, 0, 0],
                "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
```

```
        "RotReactVars" = [],
        "TranReactVars" = []]:
# Mech Frame 6 (C2)
rMData["C2"] := "SubIdent", "mRigidBodyFrame",
    "Description", "C2",
    "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
    "NodeMap", [[DOM_MT, "COM_2", "C2"], [DOM_MR, "mGND", "COM_2", "C2"]],
    "Params", ["TranConsts" = <rc2,0,0>,
        "RotConsts" = [0, 0, 0],
        "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
        "RotReactVars" = [],
        "TranReactVars" = []]:
# Rigid Body "Arm": ,
rMData["Arm"] :=
    "SubIdent", "mRigidBody",
    "Description", "Rigid Body",
    "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 1]],
    "NodeMap", [[DOM_MT, "mGND", "COM_3"], [DOM_MR, "mGND", "COM_3"]],
    "Params", ["Mass" = m3,
        "Inertia" =      [[Jxx_3,0,0],
            [0,Jyy_3,0],
            [0,0,Jzz_3]],
        "TranVars" = [x_3, y_3, z_3],
        "RotVars" = [zeta_3, eta_3, xi_3], "RotType" = "EA123",
        "AngVelVars" = [wx_3, wy_3, wz_3], "AngVelType" = "End"]:
# Mech Frame 8 (D3)
rMData["D3"] := "SubIdent", "mRigidBodyFrame",
    "Description", "D3",
    "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
    "NodeMap", [[DOM_MT, "COM_3", "D3"], [DOM_MR, "mGND", "COM_3", "D3"]],
    "Params", ["TranConsts" = <rc3,0,0>,
        "RotConsts" = [0, Pi, 0],
        "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
        "RotReactVars" = [],
```

```
                "TranReactVars" = []]:
# Mech Frame 9 (C3)
rMData["C3"] := "SubIdent", "mRigidBodyFrame",
        "Description", "C3",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "COM_3", "C3"], [DOM_MR, "mGND", "COM_3", "C3"]],
        "Params", ["TranConsts" = <-Lc3,0,0>,
                "RotConsts" = [0, 0, 0],
                "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
                "RotReactVars" = [],
                "TranReactVars" = []]:
# Rigid Body "Wrist-1": ,
rMData["Wrist-1"] :=
        "SubIdent", "mRigidBody",
        "Description", "Rigid Body",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 1]],
        "NodeMap", [[DOM_MT, "mGND", "COM_4"], [DOM_MR, "mGND", "COM_4"]],
        "Params", ["Mass" = m4,
                "Inertia" =     [[Jxx_4,0,0],
                        [0,Jyy_4,0],
                        [0,0,Jzz_4]],
                "TranVars" = [x_4, y_4, z_4],
                "RotVars" = [zeta_4, eta_4, xi_4], "RotType" = "EA123",
                "AngVelVars" = [], "AngVelType" = "Current"]:
# Mech Frame 11 (D4)
rMData["D4"] := "SubIdent", "mRigidBodyFrame",
        "Description", "D4",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "COM_4", "D4"], [DOM_MR, "mGND", "COM_4", "D4"]],
        "Params", ["TranConsts" = <0,0,0>,
                "RotConsts" = [0, 0, 0],
                "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
                "RotReactVars" = [],
                "TranReactVars" = []]:
```

```
# Mech Frame 12 (E4)
rMData["E4"] := "SubIdent", "mRigidBodyFrame",
        "Description", "E4",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "COM_4", "E4"], [DOM_MR, "mGND", "COM_4", "E4"]],
        "Params", ["TranConsts" = <0, 0, 0>,
                "RotConsts" = [0, 0, 0],
                "RotAxes" = [<1, 0, 0>, <0, 1, 0>, <0, 0, 1>],
                "RotReactVars" = [],
                "TranReactVars" = []]:
# Rigid Body "Waist": ,
rMData["Waist"] :=
        "SubIdent", "mRigidBody",
        "Description", "Rigid Body",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 1]],
        "NodeMap", [[DOM_MT, "mGND", "COM_1"], [DOM_MR, "mGND", "COM_1"]],
        "Params", ["Mass" = m1,
                "Inertia" =         [[Jxx_1,0,0],
                        [0,Jyy_1,0],
                        [0,0,Jzz_1]],
                "TranVars" = [x_1, y_1, z_1],
                "RotVars" = [zeta_1, eta_1, xi_1], "RotType" = "EA123",
                "AngVelVars" = [wx_1, wy_1, wz_1], "AngVelType" = "End"]:
# Mech Frame 14 (A1)
rMData["A1"] := "SubIdent", "mRigidBodyFrame",
        "Description", "A1",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "COM_1", "A1"], [DOM_MR, "mGND", "COM_1", "A1"]],
        "Params", ["TranConsts" = <0,0,0>,
                "RotConsts" = [0, 0, 0],
                "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
                "RotReactVars" = [],
                "TranReactVars" = []]:
# Mech Frame 15 (B1)
```

```
rMData["B1"] := "SubIdent", "mRigidBodyFrame",
        "Description", "B1",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "COM_1", "B1"], [DOM_MR, "mGND", "COM_1", "B1"]],
        "Params", ["TranConsts" = <0,0,0>,
                "RotConsts" = [0, 0, 0],
                "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
                "RotReactVars" = [],
                "TranReactVars" = []]:

# Revolute joint "joint 1":
rMData["joint 1"] :=
        "SubIdent", "mRevJt",
        "Description", "Revolute joint",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "mGND", "A1"], [DOM_MR, "mGND", "mGND", "A1"]],
        "Params", ["RotVars" = [theta_1], "RotReactVars" = [M1_1, M2_1], "TranReactVars" = [Fx_1, Fy_1, Fz_1],
                "RotAxis" = <0,0,1>, "ReactAxis1" = <1,0,0>,
                "K"=0, "Ang0"=0, "D"=0, "Moment"=T1,
                "RotDrivers" = [f(t)], "RotDrvReactVars" = [Torque]]:
# Revolute joint "joint 2":
rMData["joint 2"] :=
        "SubIdent", "mRevJt",
        "Description", "Revolute joint",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "B1", "B2"], [DOM_MR, "mGND", "B1", "B2"]],
        "Params", ["RotVars" = [theta_2], "RotReactVars" = [M1_2, M2_2], "TranReactVars" = [Fx_2, Fy_2, Fz_2],
                "RotAxis" = <0,0,1>, "ReactAxis1" = <1,0,0>,
                "K"=0, "Ang0"=0, "D"=0, "Moment"=T2,
                "RotDrivers" = [f(t)], "RotDrvReactVars" = [Torque]]:
# Revolute joint "joint 3":
rMData["joint 3"] :=
        "SubIdent", "mRevJt",
        "Description", "Revolute joint",
```

```
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "C2", "C3"], [DOM_MR, "mGND", "C2", "C3"]],
        "Params", ["RotVars" = [theta_3], "RotReactVars" = [M1_3, M2_3], "TranReactVars" = [Fx_3, Fy_3, Fz_3],
                "RotAxis" = <0,0,1>, "ReactAxis1" = <1,0,0>,
                "K"=0, "Ang0"=0, "D"=0, "Moment"=T3,
                "RotDrivers" = [f(t)], "RotDrvReactVars" = [Torque]]:
# Revolute joint "joint 4-rotate":
rMData["joint 4-rotate"] :=
        "SubIdent", "mRevJt",
        "Description", "Revolute joint",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "D3", "D4"], [DOM_MR, "mGND", "D3", "D4"]],
        "Params", ["RotVars" = [theta_4], "RotReactVars" = [M1_4, M2_4], "TranReactVars" = [Fx_4, Fy_4, Fz_4],
                "RotAxis" = <0,0,1>, "ReactAxis1" = <1,0,0>,
                "K"=0, "Ang0"=0, "D"=0, "Moment"=T4,
                "RotDrivers" = [f(t)], "RotDrvReactVars" = [Torque]]:
# Rigid Body "Wrist-2": ,
rMData["Wrist-2"] :=
        "SubIdent", "mRigidBody",
        "Description", "Rigid Body",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 1]],
        "NodeMap", [[DOM_MT, "mGND", "COM_5"], [DOM_MR, "mGND", "COM_5"]],
        "Params", ["Mass" = m5,
                "Inertia" =         [[Jxx_5,0,0],
                         [0,Jyy_5,0],
                         [0,0,Jzz_5]],
                "TranVars" = [x_5, y_5, z_5],
                "RotVars" = [zeta_5, eta_5, xi_5], "RotType" = "EA123",
                "AngVelVars" = [wx_5, wy_5, wz_5], "AngVelType" = "End"]:
# Mech Frame 17 (E5)
rMData["E5"] := "SubIdent", "mRigidBodyFrame",
        "Description", "E5",
        "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
        "NodeMap", [[DOM_MT, "COM_5", "E5"], [DOM_MR, "mGND", "COM_5", "E5"]],
```

```
      "Params", ["TranConsts" = <0,0,0>,
              "RotConsts" = [0, 0, 0],
              "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
              "RotReactVars" = [],
              "TranReactVars" = []]:
# Mech Frame 18 (F5)
rMData["F5"] := "SubIdent", "mRigidBodyFrame",
      "Description", "F5",
      "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
      "NodeMap", [[DOM_MT, "COM_5", "F5"], [DOM_MR, "mGND", "COM_5", "F5"]],
      "Params", ["TranConsts" = <0,0,0>,
              "RotConsts" = [0, 0, 0],
              "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
              "RotReactVars" = [],
              "TranReactVars" = []]:
# Revolute joint "joint 5-pitch":
rMData["joint 5-pitch"] :=
      "SubIdent", "mRevJt",
      "Description", "Revolute joint",
      "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
      "NodeMap", [[DOM_MT, "E4", "E5"], [DOM_MR, "mGND", "E4", "E5"]],
      "Params", ["RotVars" = [theta_5], "RotReactVars" = [M1_5, M2_5], "TranReactVars" = [Fx_5, Fy_5, Fz_5],
              "RotAxis" = <0,0,1>, "ReactAxis1" = <1,0,0>,
              "K"=0, "Ang0"=0, "D"=0, "Moment"=T5,
              "RotDrivers" = [f(t)], "RotDrvReactVars" = [Torque]]:
# Rigid Body "Wrist-3": ,
rMData["Wrist-3"] :=
      "SubIdent", "mRigidBody",
      "Description", "Rigid Body",
      "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 1]],
      "NodeMap", [[DOM_MT, "mGND", "COM_6"], [DOM_MR, "mGND", "COM_6"]],
      "Params", ["Mass" = m6,
              "Inertia" =        [[Jxx_6,0,0],
                      [0,Jyy_6,0],
```

```
            [0,0,Jzz_6]],
        "TranVars" = [x_6, y_6, z_6],
        "RotVars" = [zeta_6, eta_6, xi_6], "RotType" = "EA123",
        "AngVelVars" = [wx_6, wy_6, wz_6], "AngVelType" = "End"]:
# Mech Frame 20 (F6)
rMData["F6"] := "SubIdent", "mRigidBodyFrame",
    "Description", "F6",
    "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
    "NodeMap", [[DOM_MT, "COM_6", "F6"], [DOM_MR, "mGND", "COM_6", "F6"]],
    "Params", ["TranConsts" = <0,0,0>,
        "RotConsts" = [0, 0, 0],
        "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
        "RotReactVars" = [],
        "TranReactVars" = []]:
# Mech Frame 21 (P)
rMData["P"] := "SubIdent", "mRigidBodyFrame",
    "Description", "P",
    "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
    "NodeMap", [[DOM_MT, "COM_6", "P"], [DOM_MR, "mGND", "COM_6", "P"]],
    "Params", ["TranConsts" = <0,0,0>,
        "RotConsts" = [0, 0, 0],
        "RotAxes" = [<1,0,0>, <0,1,0>, <0,0,1>],
        "RotReactVars" = [],
        "TranReactVars" = []]:
# Revolute joint "joint 6-roll":
rMData["joint 6-roll"] :=
    "SubIdent", "mRevJt",
    "Description", "Revolute joint",
    "TreeEdges", [0, [DOM_MT, 1], [DOM_MR, 2]],
    "NodeMap", [[DOM_MT, "F5", "F6"], [DOM_MR, "mGND", "F5", "F6"]],
    "Params", ["RotVars" = [theta_6], "RotReactVars" = [M1_6, M2_6], "TranReactVars" = [Fx_6, Fy_6, Fz_6],
        "RotAxis" = <0,0,1>, "ReactAxis1" = <1,0,0>,
        "K"=0, "Ang0"=0, "D"=0, "Moment"=T6,
        "RotDrivers" = [f(t)], "RotDrvReactVars" = [Torque]]:
```

```
end use:
        # -============== End of model description ==============-
```

Appendix F

Behaviour of ADAMS Model to the Given Motions

The dynamic behaviour of the robot for joint 3, parts 7, 11 and 12, considering Figure 5-2, are also represented in the following diagrams:

Joint 3 (revolute) between part 14 and part 7

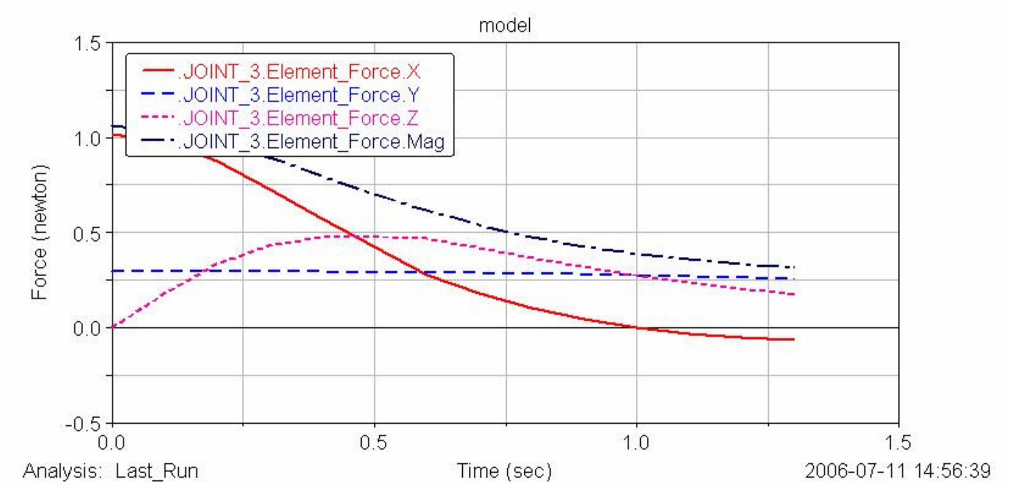

Figure F-1: The x, y, z components and magnitude of the element force for joint 3.

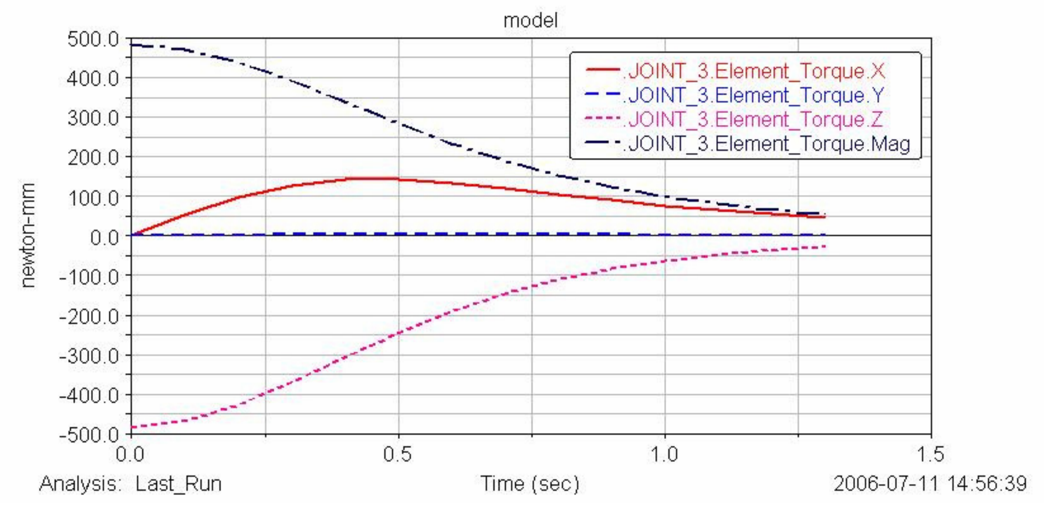

Figure F-2: The x, y, z components and magnitude of the element torque for joint 3.

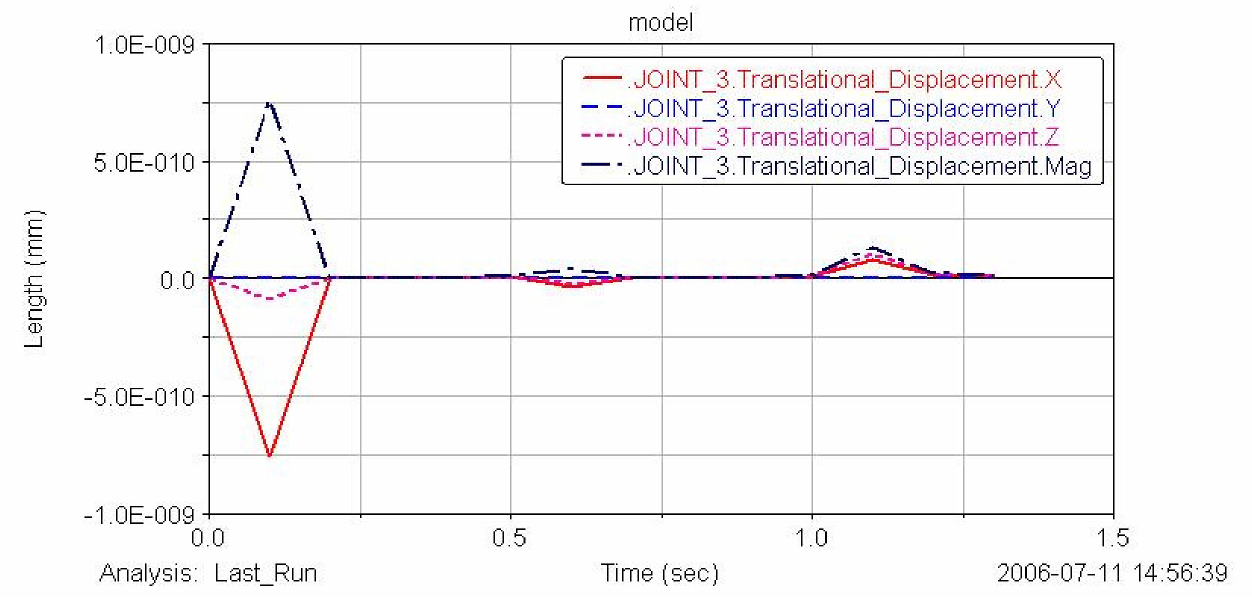

Figure F-3: The x, y, z components and magnitude of the translational displacement for joint 3.

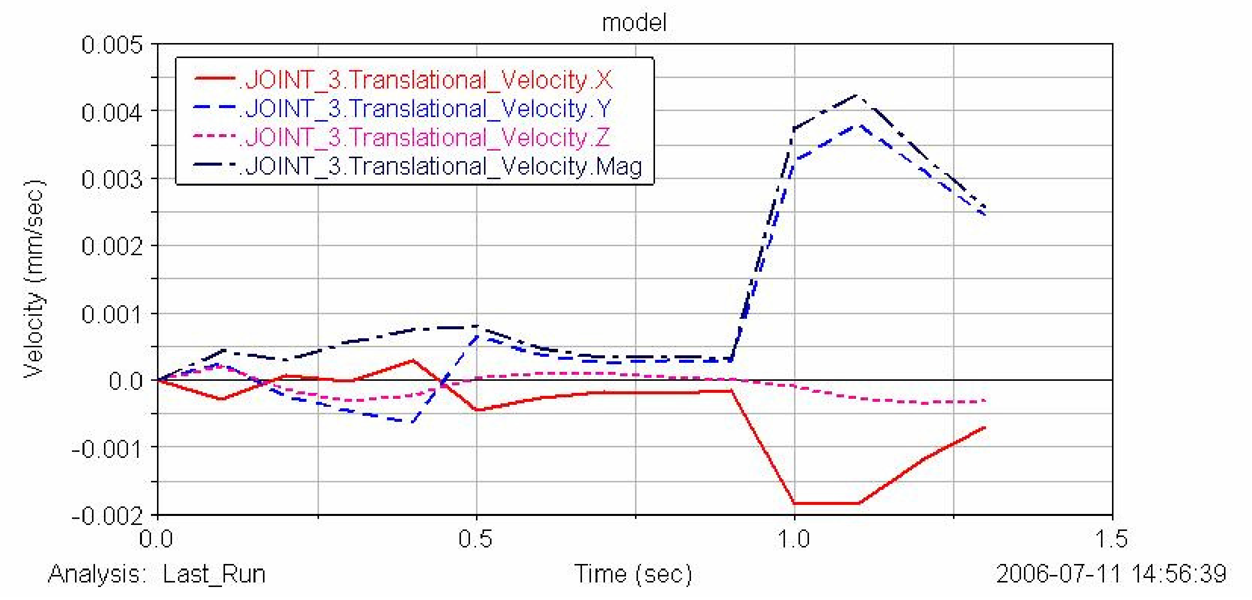

Figure F-4: The x, y, z components and magnitude of the translational velocity for joint 3.

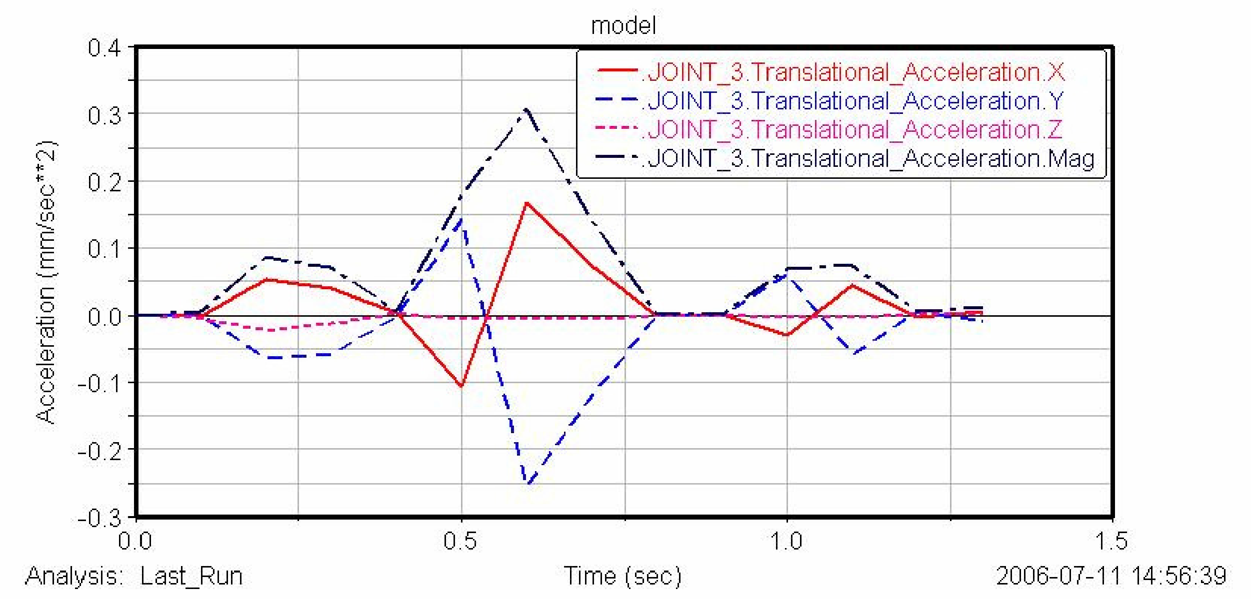

Figure F-5: The x, y, z components and magnitude of the translational acceleration for joint 3.

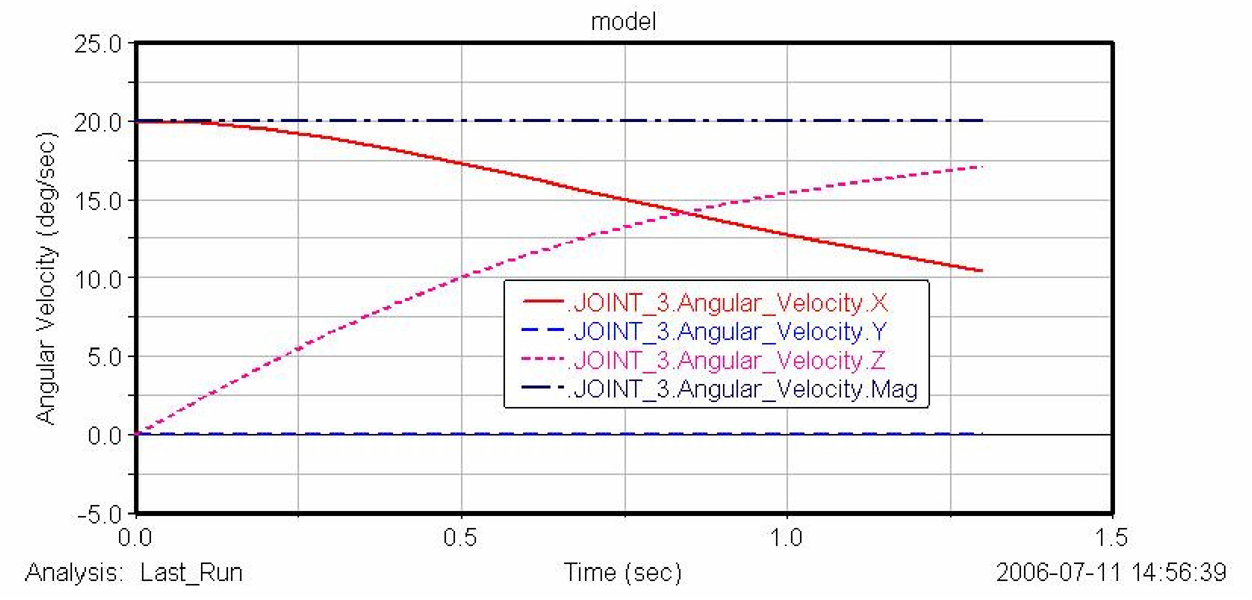

Figure F-6: The x, y, z components and magnitude of the angular velocity for joint 3.

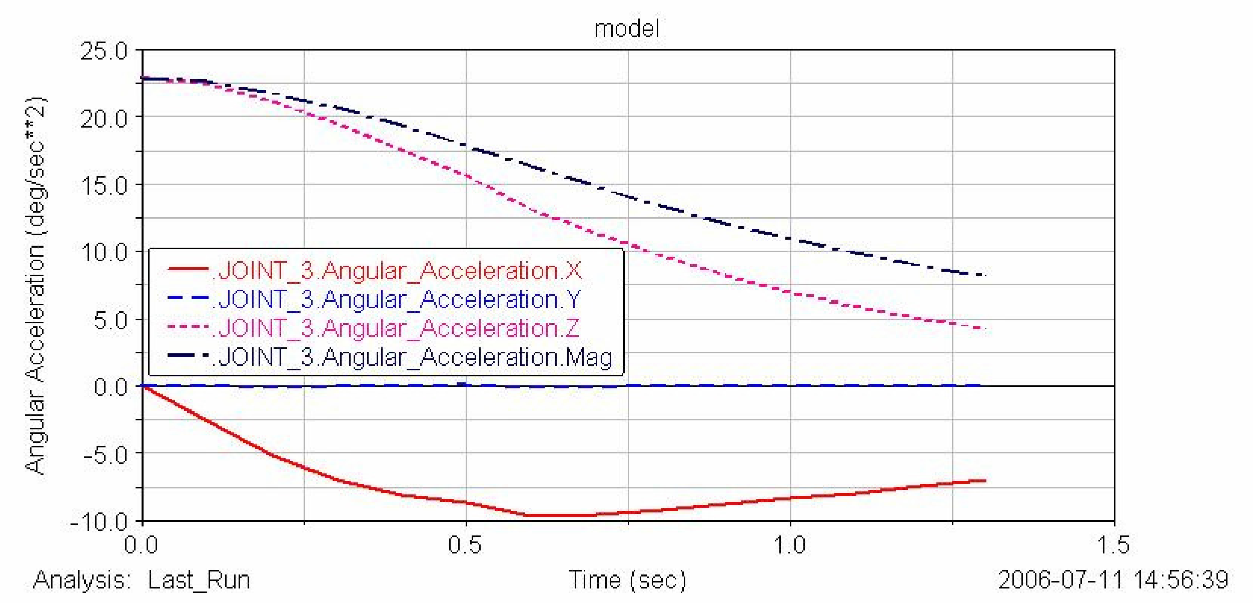

Figure F-7: The x, y, z components and magnitude of the angular acceleration for joint 3.

Part 7: Link

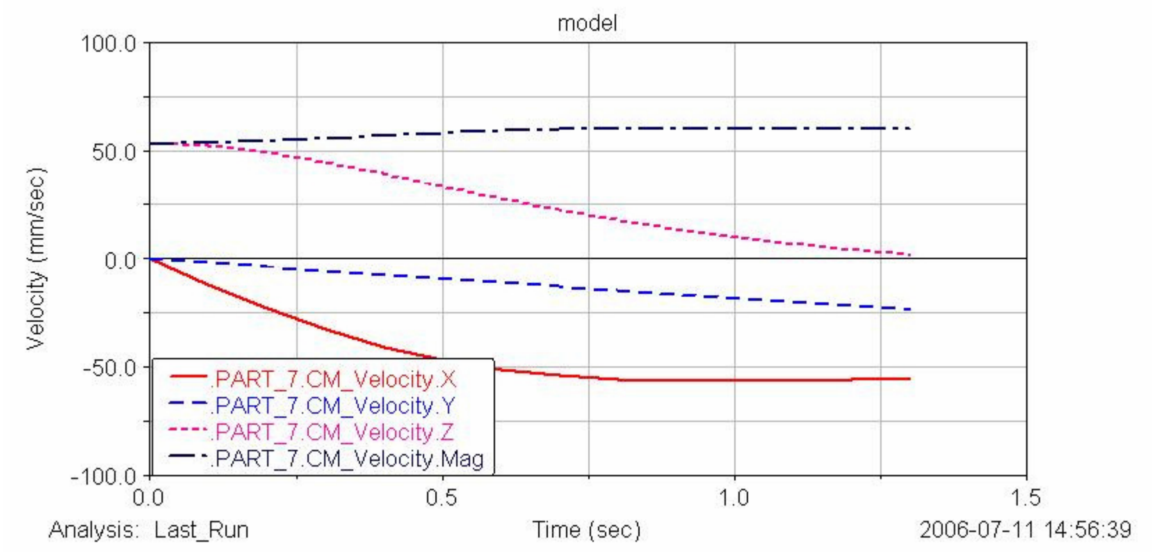

Figure F-8: The x, y, z components and magnitude of the velocity of CM of part 7.

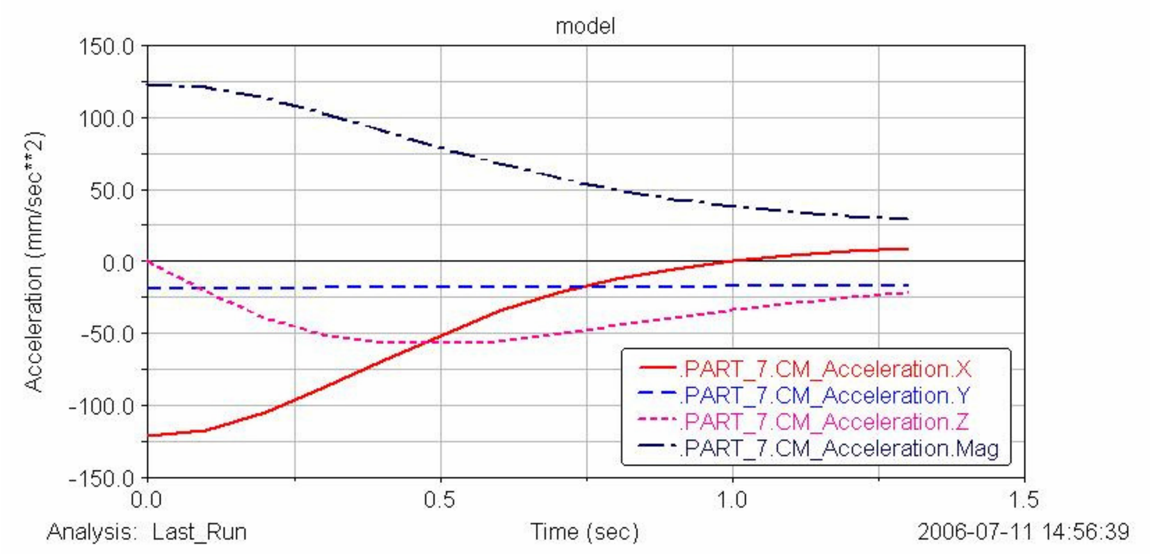

Figure F-9: The x, y, z components and magnitude of the acceleration of CM of part 7.

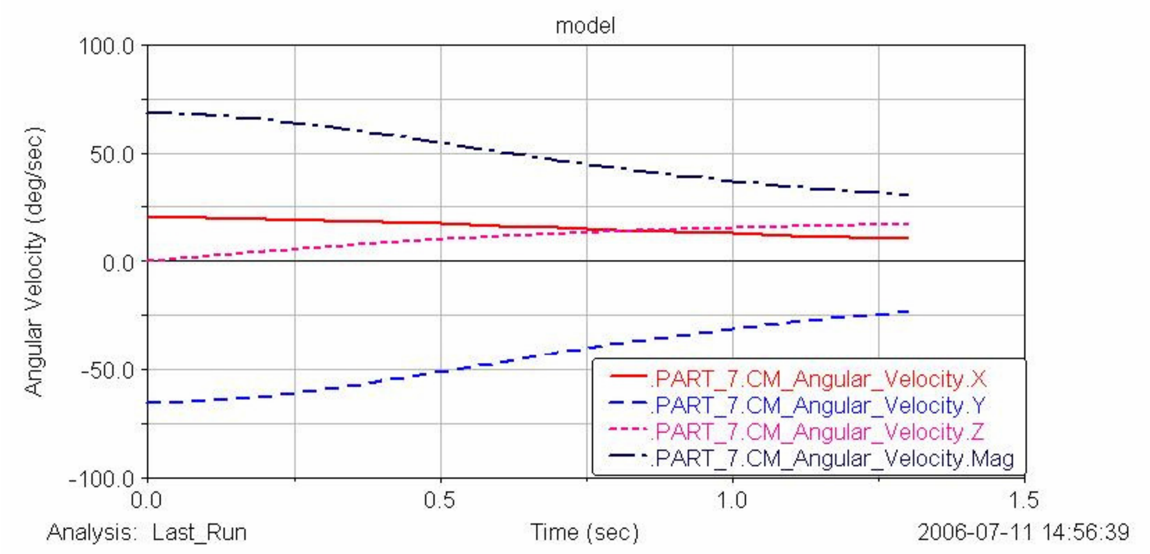

Figure F-10: The x, y, z components and magnitude of the angular velocity of CM of part 7.

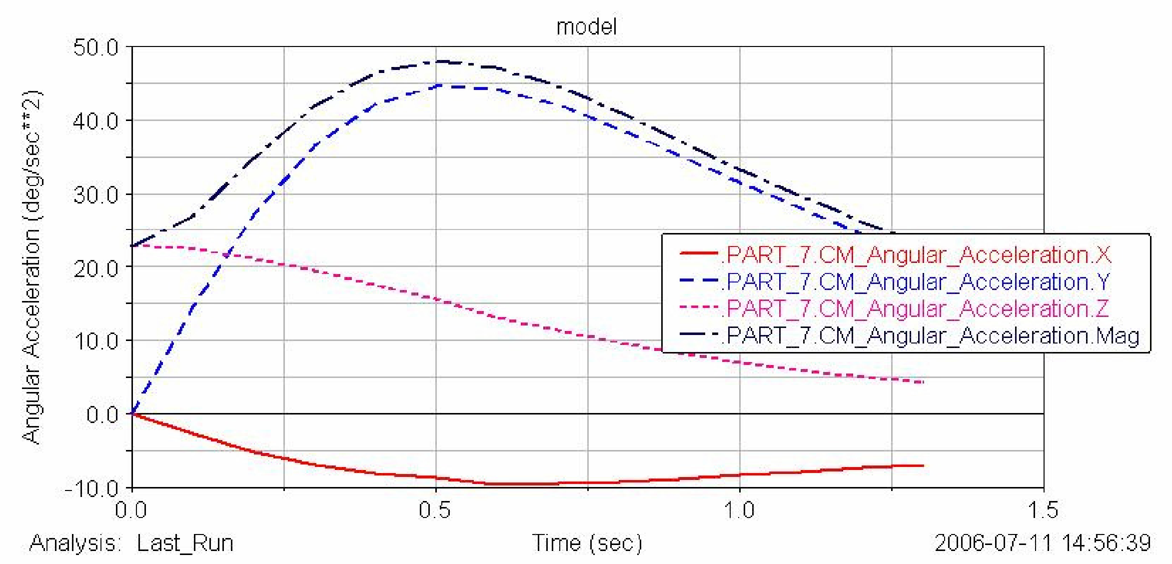

Figure F-11: The x, y, z components and magnitude of the angular acceleration of CM of part 7.

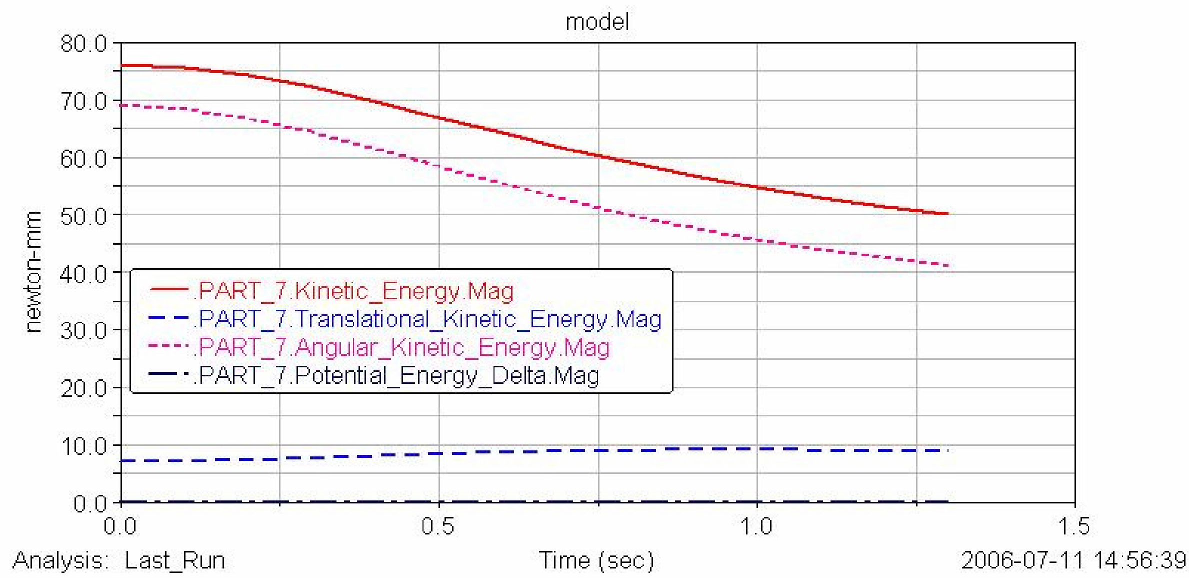

Figure F-12: Kinetic energy, Translational kinetic energy and angular kinetic energy and potential energy of part 7.

Part 11 (link):

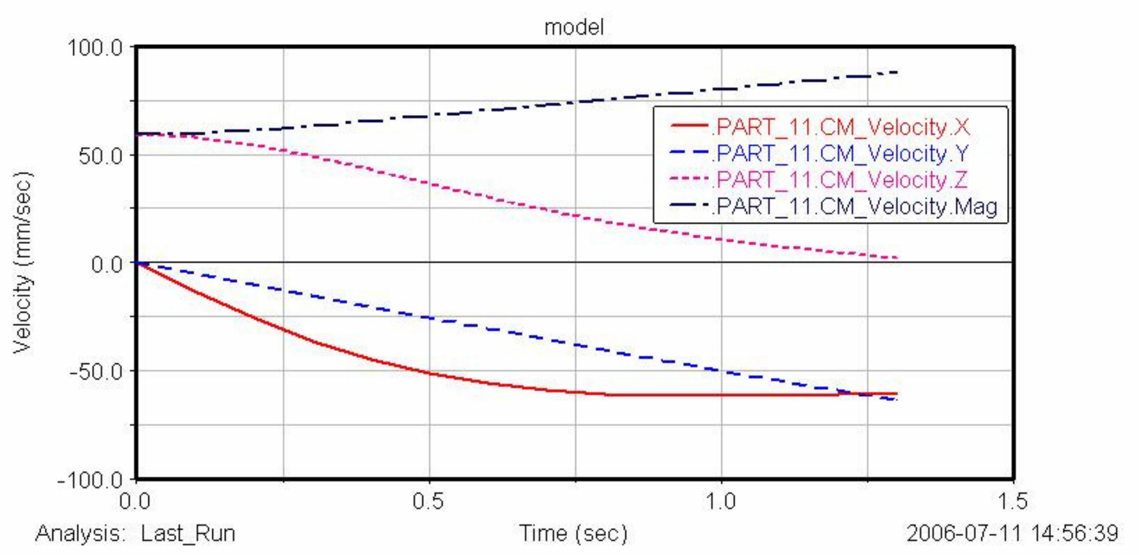

Figure F-13: The x, y, z components and magnitude of the velocity of CM of part 11.

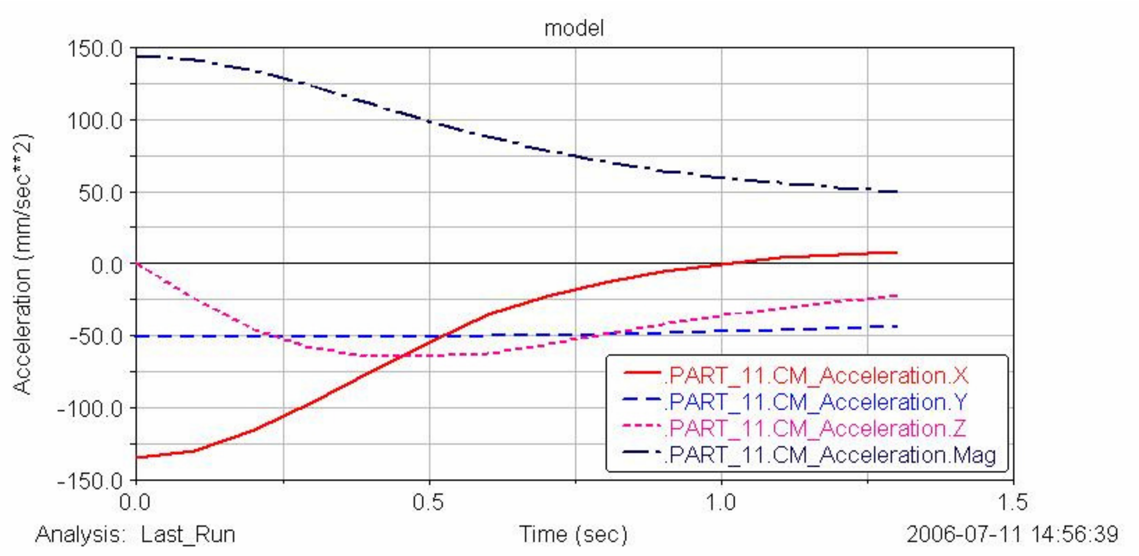

Figure F-14: The x, y, z components and magnitude of the acceleration of CM of part 11.

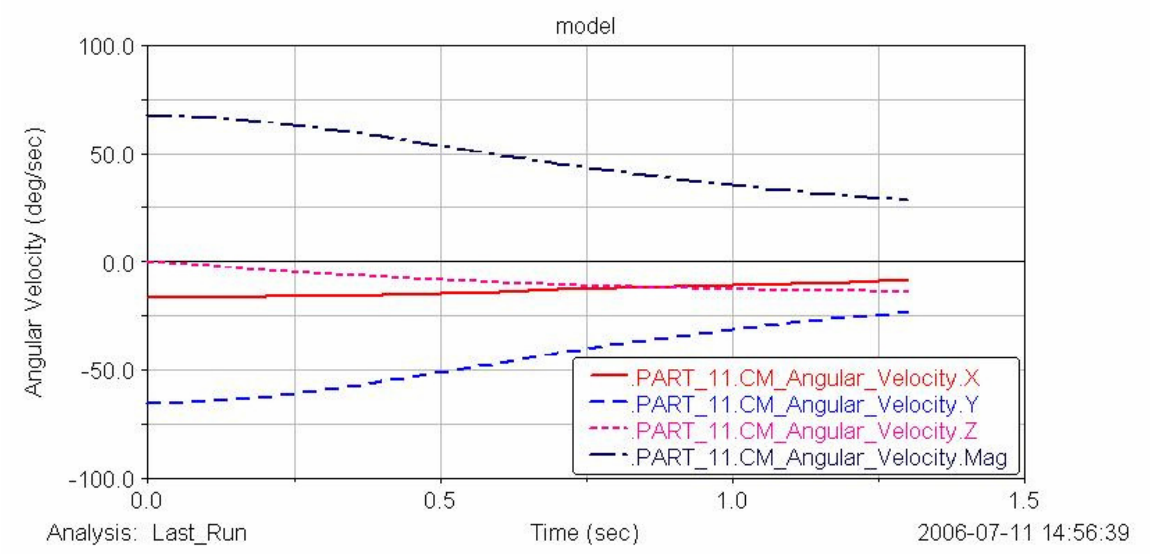

Figure F-15: The x, y, z components and magnitude of the angular velocity of CM of part 11.

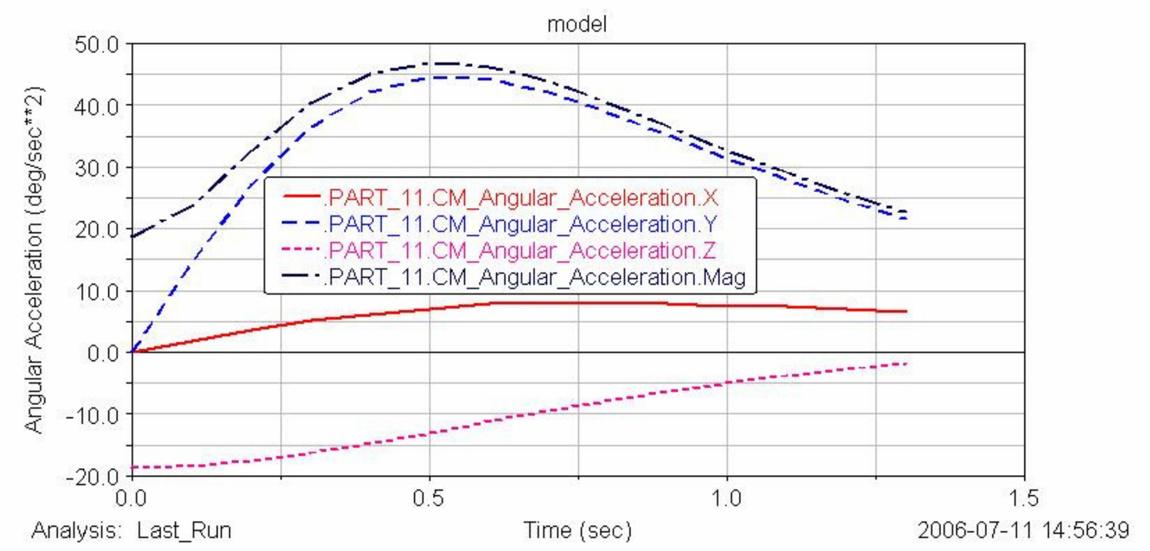

Figure F-16: The x, y, z components and magnitude of the angular acceleration of CM of part 11.

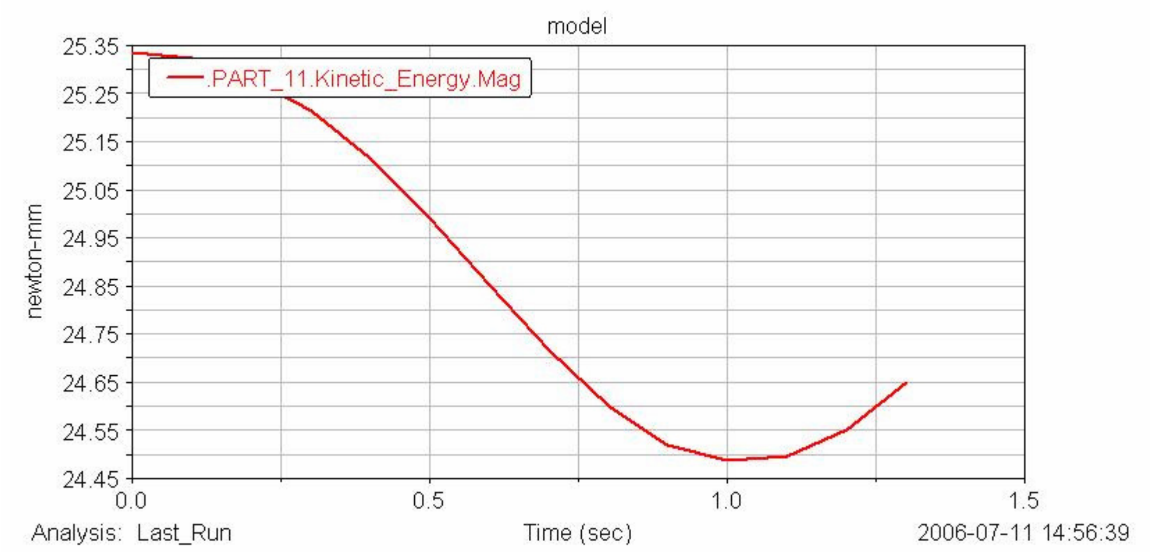

Figure F-17: The kinetic energy of the part 11.

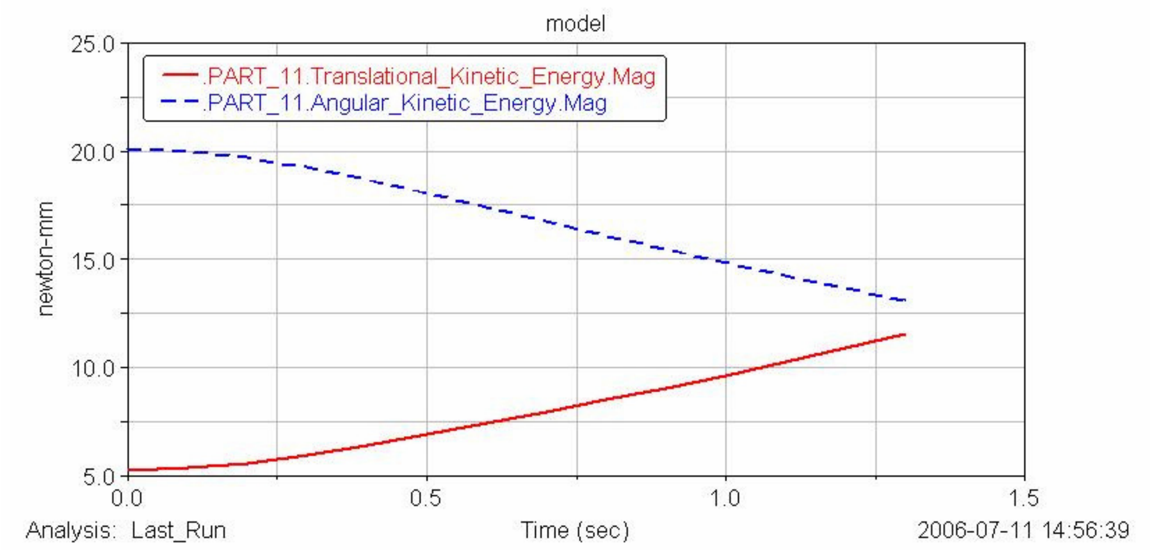

Figure F-18: The translational and angular kinetic energy of part 11.

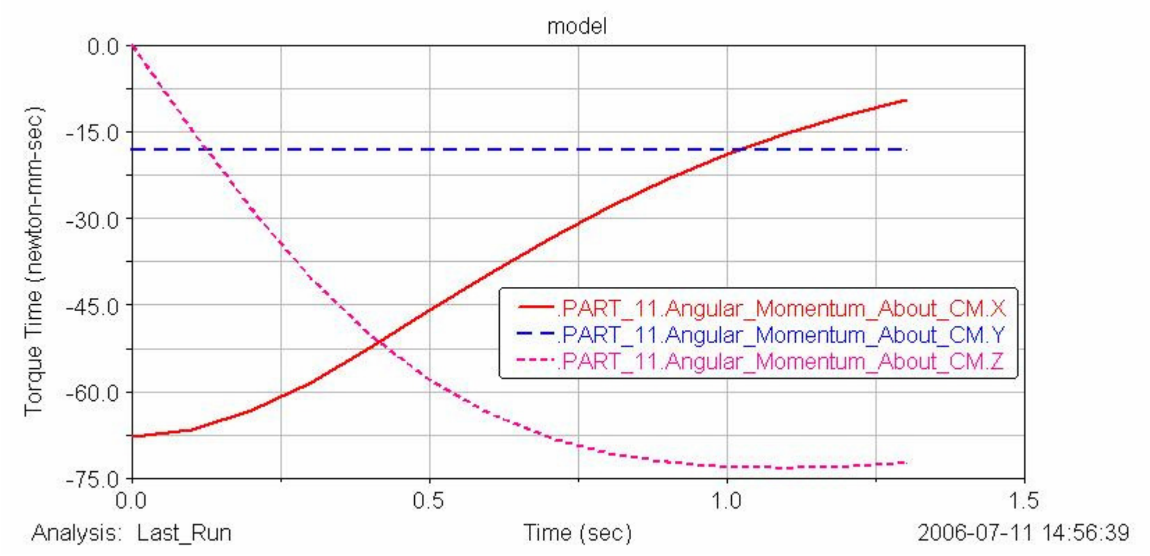

Figure F-19: The x, y, and z components of the angular momentum about CM of part 11.

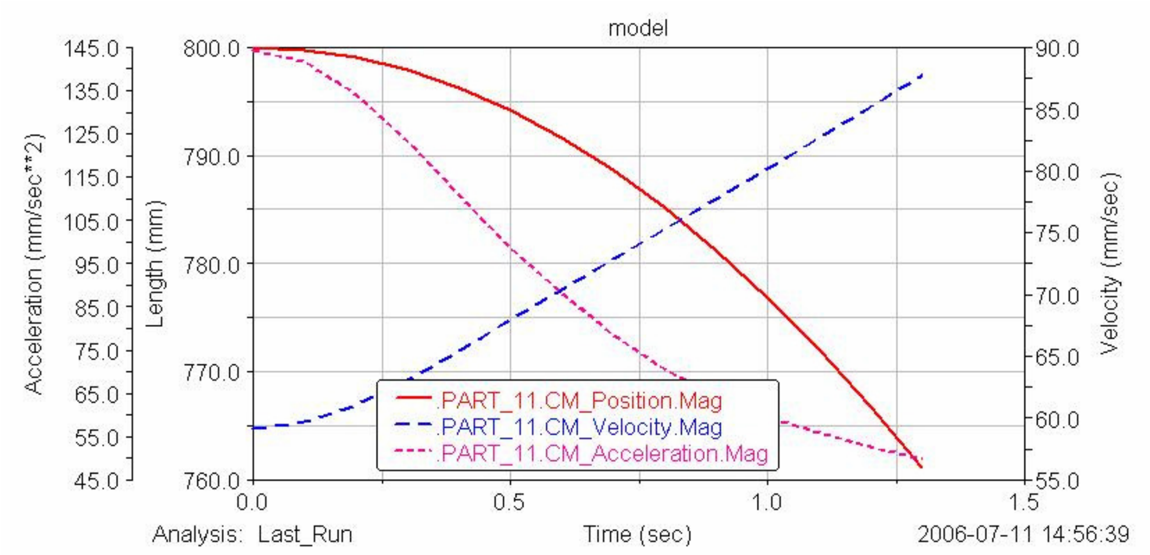

Figure F-20: The magnitudes of the position, velocity and acceleration of CM of part 11.

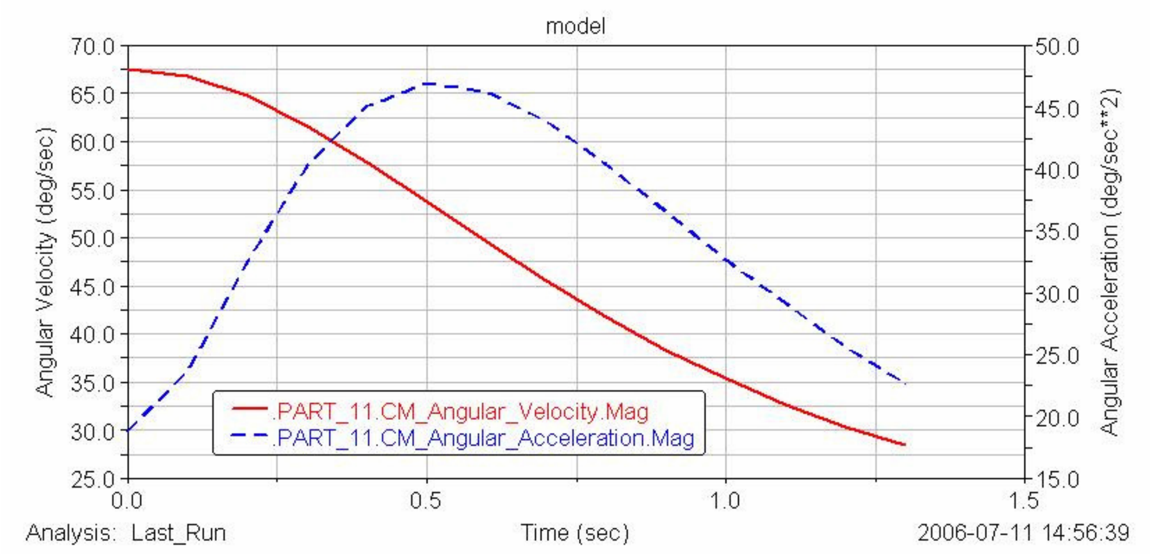

Figure F-21: The magnitudes of the angular velocity and acceleration of CM of part 11.

Part 12 (wrist)

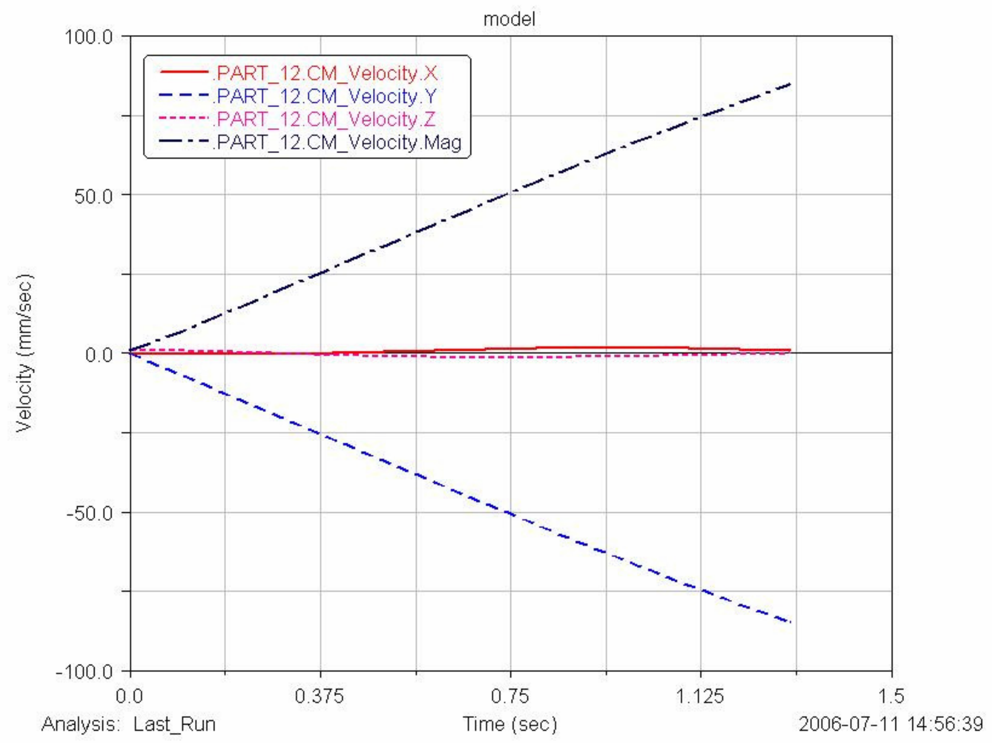

Figure F-22: The x, y, and z components of velocity of CM of part 12.

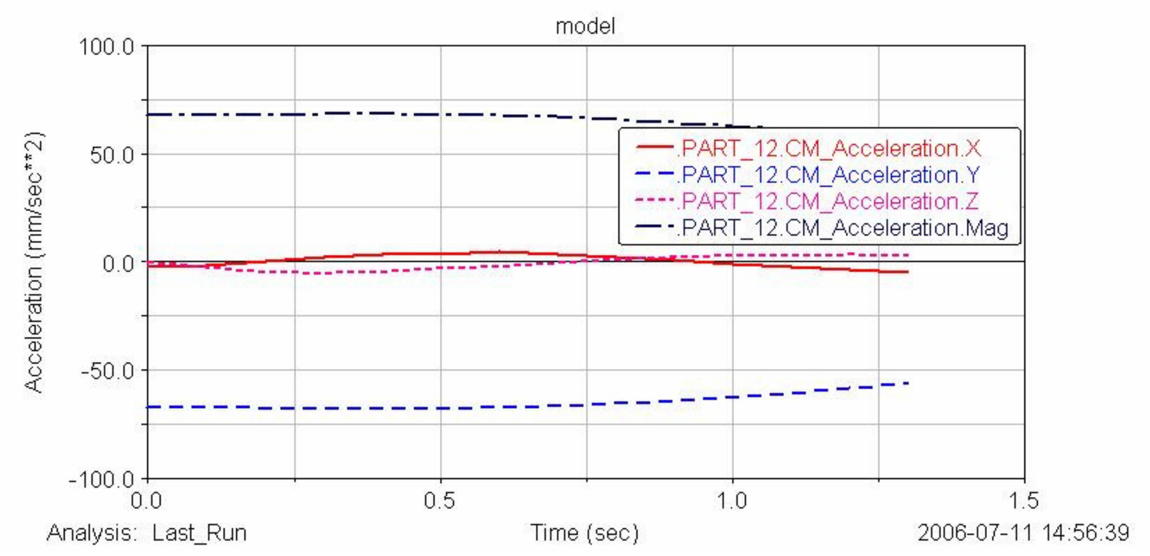

Figure F-23: The x, y, and z components of acceleration of CM of part 12.

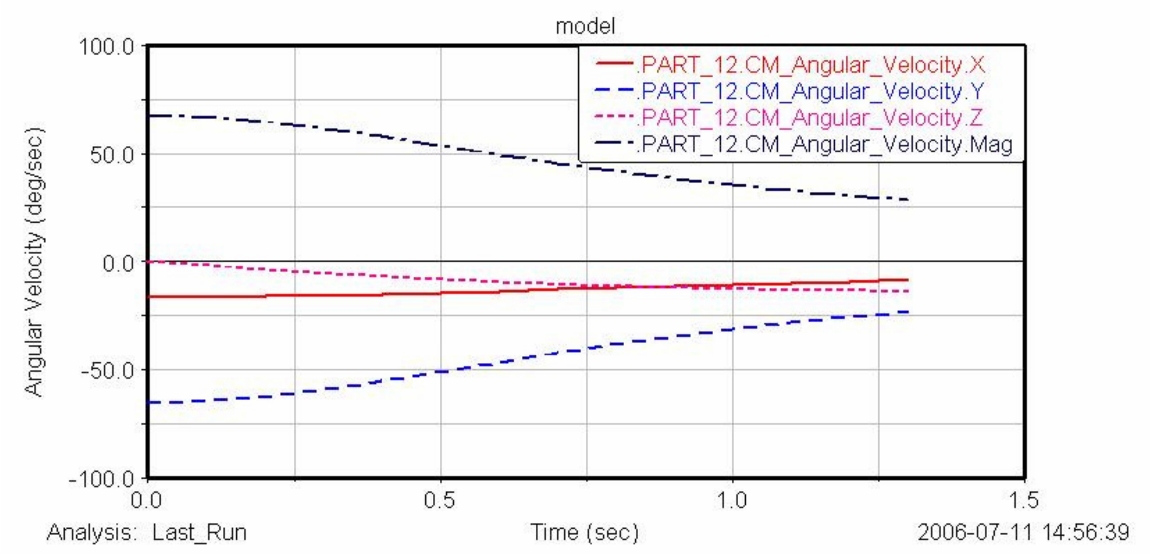

Figure F-24: The x, y, and z components of the angular velocity of CM of part 12.

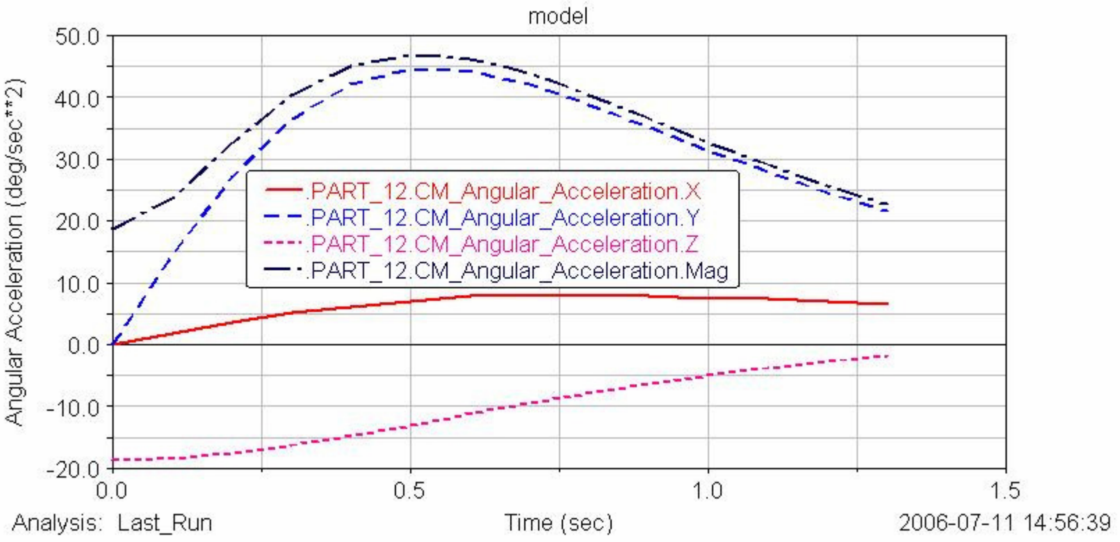

Figure F-25: The x, y, and z components of the angular acceleration of CM of part 12.

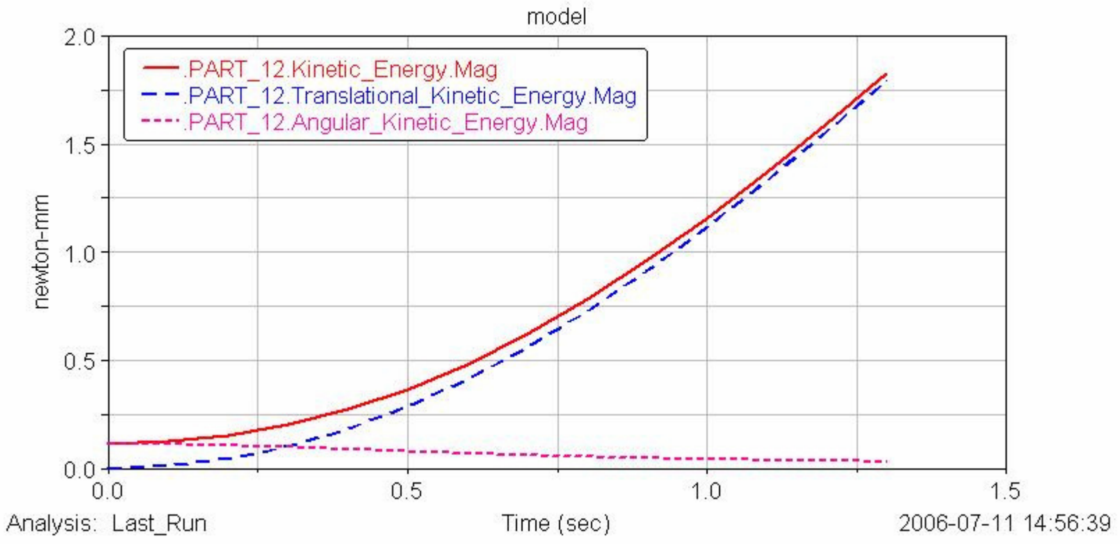

Figure F-26: The kinetic energy, translational kinetic energy and angular kinetic energy of part 12.

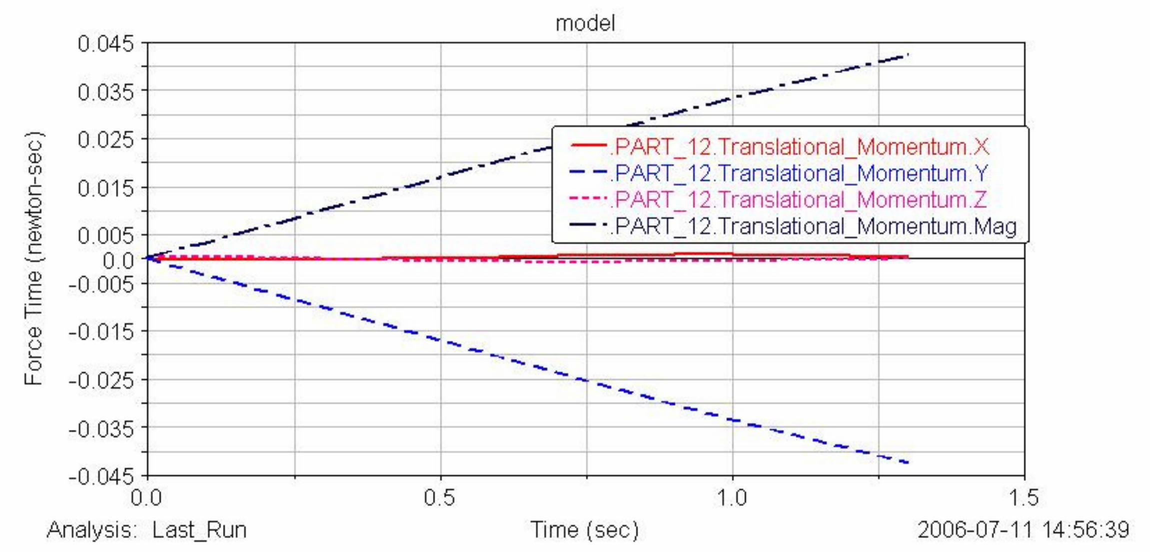

Figure F-27: The x, y, z component and the magnitude of the translational momentum of part 12.

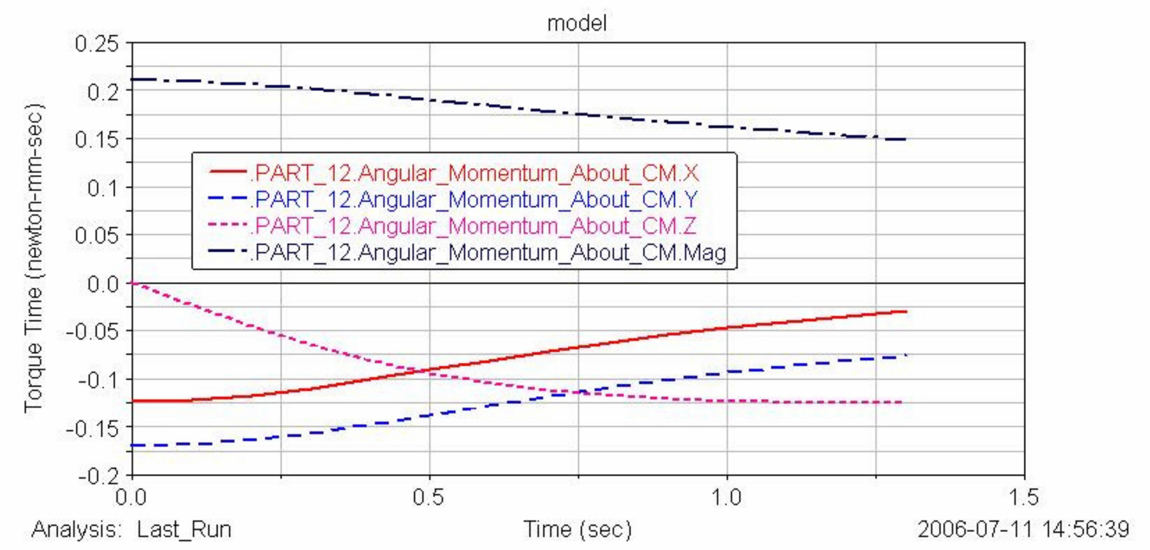

Figure F-28: The x, y, z component and the magnitude of the angular momentum about CM of part 12

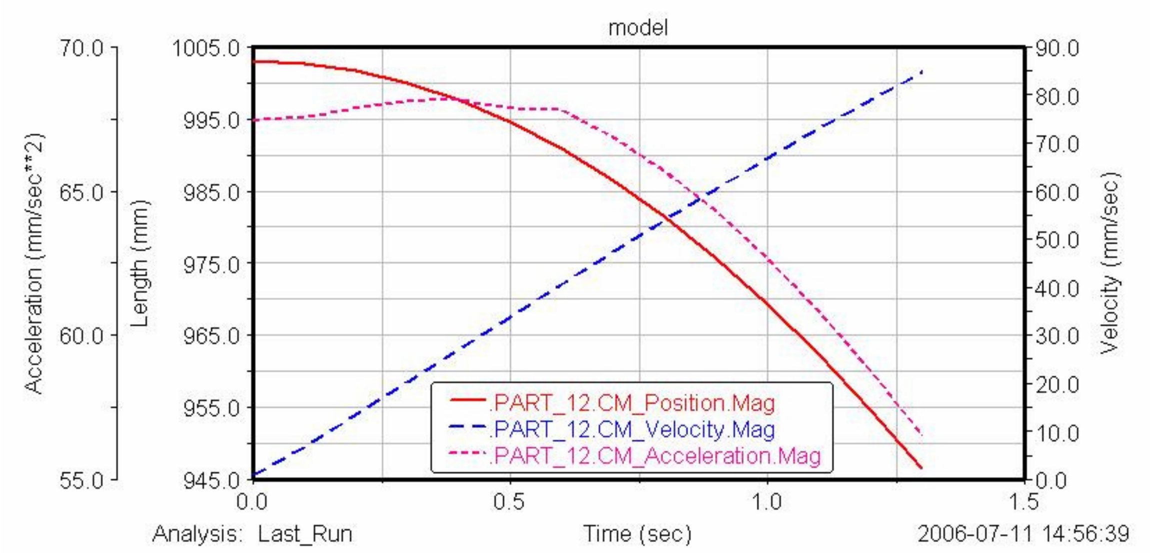

Figure F-29: Magnitudes of the Position, Velocity and Acceleration of CM of part 12.

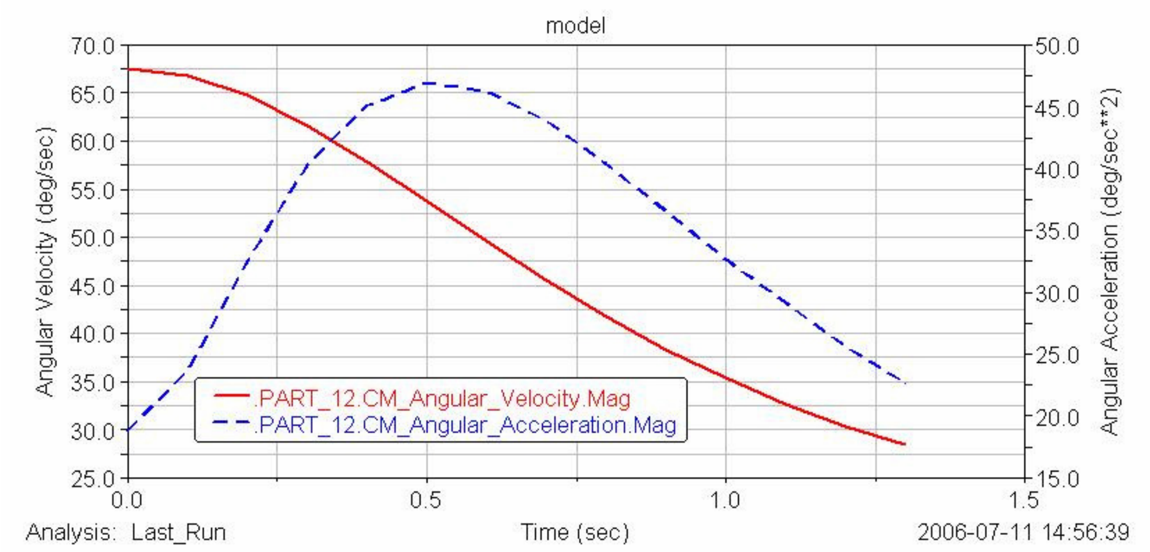

Figure F-30: Magnitudes of the angular Velocity and Acceleration of CM of part 12.

Appendix G

ADAMS/MATLAB Interface

Based on the information of .m file in MATLAB, the adams_sub block was created, as shown in Figure G-2 and the input and outputs of the model appearing in the sub-blocks are shown in Figure G-1.

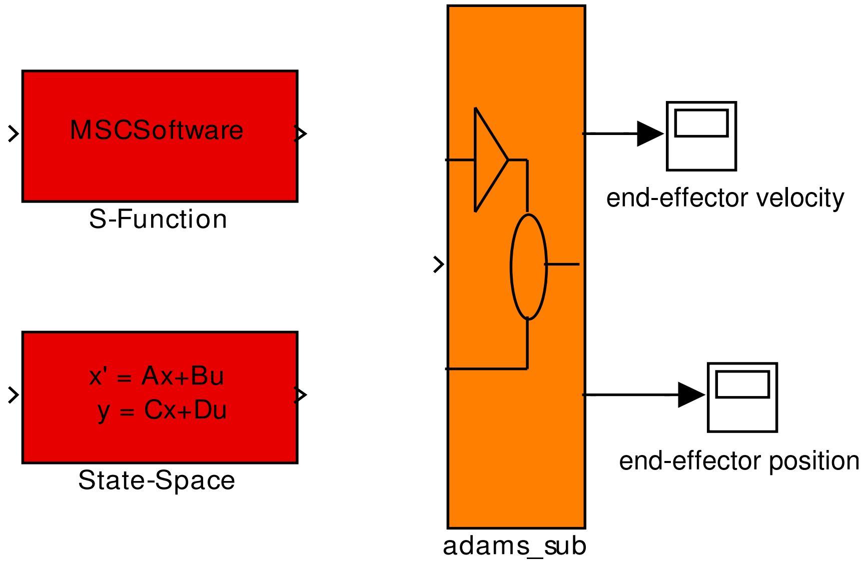

Figure G-1: The block of adams_sub containing the S-Function.

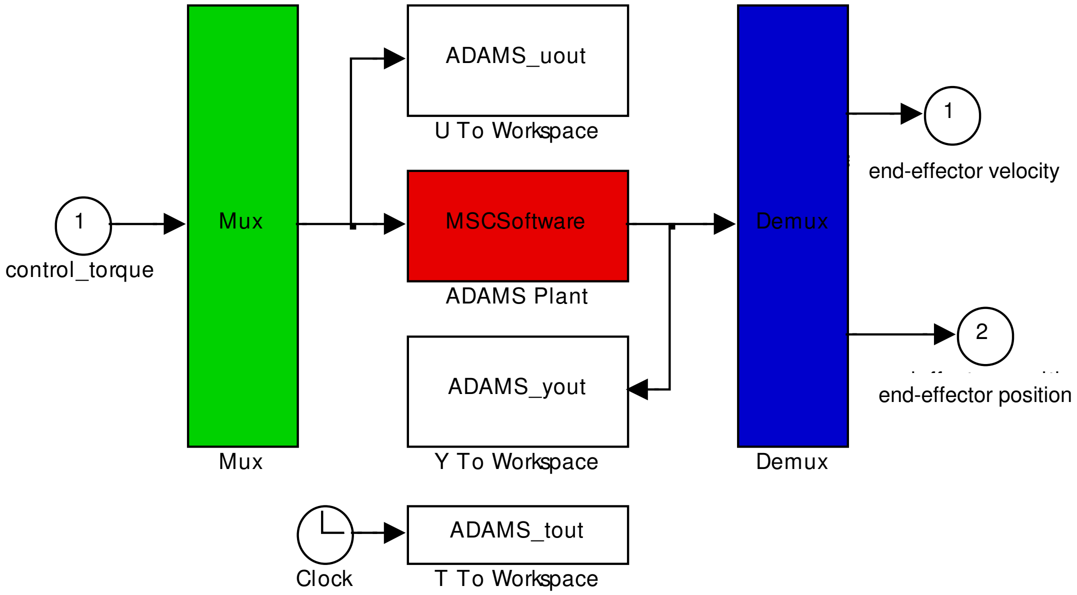

Figure G-2: Defined input and outputs of the model appearing in the sub-blocks.

The names appear according to the information read from the following .m file:

ADAMS/MATLAB Interface

```
% ADAMS / MATLAB Interface - Release 2005.2.0
machine=computer;
if strcmp(machine, 'SOL2')
   arch = 'ultra';
elseif strcmp(machine, 'SGI')
   arch = 'irix32';
elseif strcmp(machine, 'GLNX86')
   arch = 'rh_linux';
elseif strcmp(machine, 'HPUX')
   arch = 'hpux11';
elseif strcmp(machine, 'IBM_RS')
   arch = 'ibmrs';
else
   arch = 'win32';
end
[flag, topdir]=dos('adams05r2 -top');
if flag == 0
  temp_str=strcat(topdir, arch);
```

```
  addpath(temp_str)
  temp_str=strcat(topdir, '/controls/', arch);
  addpath(temp_str)
  temp_str=strcat(topdir, '/controls/', 'matlab');
  addpath(temp_str)
  ADAMS_sysdir = strcat(topdir, '');
else
  addpath( 'C:\MSC~1.SOF\MSC~1.ADA\2005r2\win32' ) ;
  addpath( 'C:\MSC~1.SOF\MSC~1.ADA\2005r2\controls/win32' ) ;
  addpath( 'C:\MSC~1.SOF\MSC~1.ADA\2005r2\controls/matlab' ) ;
  ADAMS_sysdir = 'C:\MSC~1.SOF\MSC~1.ADA\2005r2\' ;
end
ADAMS_exec = '' ;
ADAMS_host = 'Zone.uwaterloo.ca' ;
ADAMS_cwd ='E:\New Folder (2)'  ;
ADAMS_prefix = 'control_01' ;
ADAMS_static = 'no' ;
ADAMS_solver_type = 'Fortran' ;
if exist([ADAMS_prefix,'.adm']) == 0
   disp( ' ' ) ;
   disp( '%%% Warning : missing ADAMS plant model file.' ) ;
   disp( '%%% Please copy the exported plant model files in working
directory.' ) ;
   disp( '%%% However,  it is OK if the simulation is TCP/IP-based.' ) ;
   disp( ' ' ) ;
end
ADAMS_init = '' ;
ADAMS_inputs  = 'control_torque' ;
ADAMS_outputs = 'endeffector_velocity!endeffector_position' ;
ADAMS_pinput  = '.model.new_control.ctrl_pinput';
ADAMS_poutput = '.model.new_control.ctrl_poutput';
ADAMS_uy_ids  = [1
                 5
                 3];
ADAMS_mode   = 'non-linear' ;
tmp_in  = decode( ADAMS_inputs  ) ;
tmp_out = decode( ADAMS_outputs ) ;
disp( ' ' ) ;
disp( '%%% INFO : ADAMS plant actuators names :' ) ;
disp( [int2str([1:size(tmp_in,1)]'),blanks(size(tmp_in,1))',tmp_in] ) ;
disp( '%%% INFO : ADAMS plant sensors   names :' ) ;
disp( [int2str([1:size(tmp_out,1)]'),blanks(size(tmp_out,1))',tmp_out] ) ;
disp( ' ' ) ;
clear tmp_in tmp_out ; % ADAMS / MATLAB Interface - Release 2005.2.0
```

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