An Affordable Robotic Arm Design for Manipulation in Tabletop Clutter

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Abstract

In this study, tabletop object manipulation in a cluttered environment using a robotic manipulator is considered. Our focus is on avoiding or manipulating other obstructions/objects to achive the given task. We propose an affordable robotic manipulator design with five degrees of freedom where the gripper constitutes one additional degree of freedom. The manipulator has approximately the same length as an adult human's arm. An accurate simulation model for ROS/Gazebo along with a preliminary motion controller is also presented.

1. Introduction

Robotic manipulation is defined as making changes to an environment using a robotic manipulator (Mason, 2001). While this is a very broad definition, it can be understood as moving (pushing, pulling, lifting, carrying etc.), deforming (drilling, cutting, etc.) or simply altering the physical state of any object using a robotic manipulator. This task involves several subtasks such as grasping objects, moving objects in the environment with respect to position, velocity, acceleration and trajectory constraints and avoiding obstacles.

In this study, we address the tabletop manipulation problem in case of clutter. Our design is expected to manipulate rotationally symmetric objects residing on a flat surface, possibly unreachable without displacing other objects first. In addition to this, the design must be as inexpensive as possible in order to lead to an affordable and simple research platform.

2. Related Work

One of the most well-known example of research-oriented manipulators is the arm of Willow Garage PR2. This robot has two 7-DOF arms, both of which have 3 DOF on the shoulder, 1 DOF on the elbow and 3 DOF on the wrist; this kinematic chain is modeled directly after the human arm. There is a gripper on the end of each arm which can open and close linearly, enabling it to pick up objects. While PR2 costs $400,000 USD at the time of writing this work, there are also lower cost designs. Michael Ferguson's Maxwell is built to perform small-scale manipulation such as playing chess; it features 5 DOF and Robotis Dynamixel series servos located at each joint (Ferguson, 2011). Stückler et al. propose a mobile service robot which has two anthropomorphic 7-DOF arms where all joints are again driven by Dynamixel servos (Stückler et al., 2009). Finally, Quigley et al. propose an interesting research-oriented design; their 7-DOF manipulator has stepper motors with elastic belt transmission for the four joints that are closer to the shoulder, increasing payload and decreasing cost to a final amount of $4135 USD (Quigley et al., 2011).

Concerning clutter, Dogar et al. propose a planner where they model the physical behavior of objects when pushed by the grasper in order to predict where the objects will move and plan the grasp accordingly (Dogar et al., 2012). Dogar and Srinivasa proceed to elaborate more on the planning stage of their previous work (Dogar & Srinivasa, 2012). Finally, Gupta and Sukhatme propose a planner with manipulation primitives to firstly scatter the clutter made of toy bricks to move them into easily manipulatable positions (Gupta & Sukhatme, 2012).

3. Proposed Solution

3.1 Hardware Design

Our proposed manipulator, seen in Figure 1, has 5 DOF: two on the shoulder, one on the elbow and two on the wrist. This is a very common configuration, but it can replicate an important portion of the manipulative abilities of the human arm when performing tabletop manipulation. The end effector is a 1-DOF gripper with a "wedge" shape when closed; therefore, it is also suitable for pushing obstacles

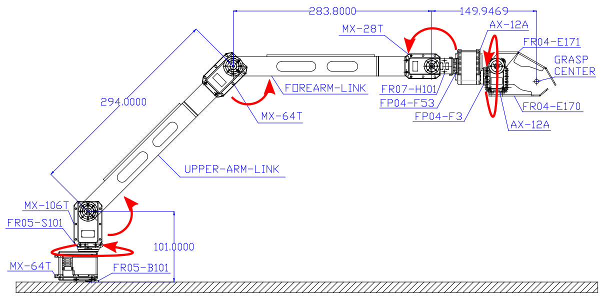

Figure 1. Mechanical design of the manipulator (Degrees of freedom shown in red, all dimensions are in mm).

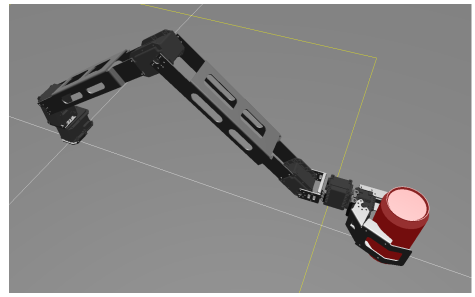

Figure 2. The simulation model of the manipulator, about to grasp a soda can.

away without grasping them.

All joints are driven by Robotis Dynamixel series servos connected over a single TTL bus; the relevant properties of the servos used in this study are provided in Table 1. Aside from the two long links that connect the shoulder to the elbow and the elbow to the wrist, all frames are commercially available in the Dynamixel frame catalog. The two custom frames are designed to be laser cut and bent out of aluminum sheets. Along with the custom made links, the total cost of the arm is projected to be $1788.2 USD.

Model	Stall Torque (Nm)	Encoder Resolution (Degrees)	Stall Current (A)
AX-12A	1.5	300/1024	1.5
MX-28T	2.5	360/4096	1.4
MX-64T	6.0	360/4096	4.1
MX-106T	8.4	360/4096	5.2

Table 1. Properties of Dynamixel Servos at 12V.

When the arm is stretched to the maximum horizontal distance from the base (727.7 mm to the approximate grasp center) the maximum allowed weight of the held object is calculated to be 902 g. Bottleneck being the shoulder lift servo, this value is calculated using the stall torques while taking the arm's own weight into account. Nominal torques are not reported in the Dynamixel datasheets; only relevant information is its being driven by a Maxon RE-MAX motor. Therefore, in order to calculate the maximum weight that the arm can effectively lift, we have obtained the approximate nominal torque per stall torque ratio from the datasheet of Maxon RE-MAX 214897 which has the same operating voltage of 12V as the servos (Maxon Motor AG, 2012). After reducing the nominal torque by approximately 12% due to friction caused by the gear train (assuming 4 gears per servo), we have concluded that the continuous nominal torque for each servo may be assumed approximately as $1/5$ of the stall torque. Furthermore, considering the short term operation notes on the aforementioned datasheet, it can be assumed that the servo will be able to apply up to approximately $2/5$ of the stall torque for brief periods of time. Given these, the arm may lift a maximum of 209 g at its furthest horizontal reach for a short amount of time; however, it may not operate continuously in the same configuration for any lifted weight.

3.2 Software Design

To be able to test the manipulator and study its limits rapidly and without damage risks, we have built a simulation model for ROS/Gazebo as seen in Figure 2. Collision maps and visual models used are 3D part models provided by Robotis. Some weight, center of gravity and inertial tensor values were provided by Robotis while the rest were calculated by BRLCAD using the 3D models with homogeneous weight distribution assumption. Viscous damping and static friction values proposed by Mensink for an AX-12A servo (Mensink, 2008) were used for all servos; to the best of our knowledge, there is no other rigorous analysis done at the time of writing.

In order to control the motion of the manipulator, its inverse kinematics is first solved analytically. Then, a gravity compensation algorithm is written to account for the arm's own weight. Given any joint configuration, we calculate the required torque for each joint to lift each link, following the kinematic chain from its end towards its beginning.

Locomotive torques are determined by a two-phase PID controller consisting of a coarse and a fine component for each joint. This method is expected to reduce travel time towards the goal and help reduce the steady state error. Passage from coarse to fine PID is controlled by a closeness threshold to the goal angle. The I components are decayed in order to overcome integral windup and the D components are passed through an IIR low pass filter in order to eliminate noise.

Finally, the weight of the lifted object is estimated using a two-phase method modeled after human behavior: The first phase is coarse estimation, where the object's estimated weight is increased by fixed increments until it is

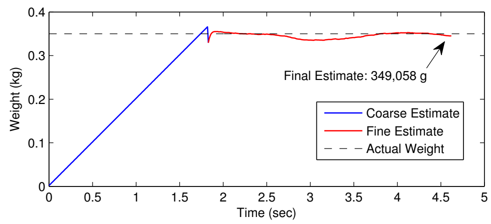

Figure 3. Example weight estimation of a 350g object.

lifted more than a predetermined distance. This phase necessarily overestimates the object's weight which is scaled down by a constant factor. Then, the fine estimation phase starts, which controls the estimated weight using a PID controller given the distance error feedback to another predetermined lift distance amount.

4. Experiments

In order to be able to perform experiments in simulation, the 30 PID coefficients ($3 + 3$ for each joint) of our controller were manually tuned, considering independent joints separately wherever possible. Then, the weight estimation PID coefficients were manually tuned. Preliminary experiments demonstrate satisfactory motion; an example can be seen online (Özgür, 2013). With the current state of our design, a given object can be grasped, lifted, and placed elsewhere.

A drawback of our design is that the control during the weight estimation process is largely dependent on the control of the joints. This disturbs the steady state estimate and delays the final estimation; such a process is given in Figure 3. Therefore, the second phase must be redesigned. Also, the PID coefficients of the joint controller must be further tuned in order to achieve a critically damped response which is currently underdamped.

5. Conclusions

Using our preliminary design, we have achieved acceptable motion in a simulated tabletop environment. However, Gazebo cannot model contact surfaces accurately enough to perform realistic grasping. For this reason, another promising simulator such as V-Rep will be considered.

In order to have a complete controller, we will implement kinetic energy compensation to provide robustness against different speeds of the links and different masses of lifted objects. The object weight estimation will be elaborated on analytically and redesigned. We will continue working on the control methods in order to achieve smooth trajectory control. Upon completing our controller, the arm will be built with actual hardware to test our software design on it.

We will then concentrate on manipulation planning and perception in clutter. We will consider methods of various authors (Dogar et al., 2012; Dogar & Srinivasa, 2012; Gupta & Sukhatme, 2012), typically applied to 7-DOF arms to plan the manipulation of irrelevant objects, and see whether modifications can be done for least possible degradation on 5 DOF. Energy consumption constraints and servo limits will also be considered during the planner design. As a final note, we will study the benefits, if any, of mounting a simple camera on our manipulator's hand. We expect that this method will improve the perception quality as the new vision source is mobile in five degrees of freedom and can also be used to improve feedback when grasping.

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