An Object Exploration Strategy for COM and Mass Determination for Robot Grasping

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***Abstract*—A strategy for object experimentation during robot grasping is presented. Specifically, a method by which object Center of Mass (COM) and mass can be determined using load force/torque sensing is developed. The strategy is tested in simulation and analyzed for robustness to noise and object reconfiguration. Simulation results show that COM can be determined exactly when noise is not present, and to sub-millimeter accuracy with reasonable noise bounds.**

***Index Terms*—object exploration, robot grasping, object property experimentation**

I. Introduction

Robot grasping is becoming increasingly important as robots are slowly moving from the factory floor into unstructured, human environments. A rich theory exists for grasp planning and analysis [1], [2], however this theory is not applicable unless certain object properties are known. Specifically, the object's COM, mass, and friction properties are essential for perfect grasp analysis and planning. Unfortunately, these pieces of information are rarely known *a priori* in an unstructured environment. If the problem is to simply immobilize a free-form object in the hand then COM location is less important: a compliant, underactuated gripper may be used and the grasp is likely to be stable. Recent research into such grippers has produced some excellent designs (see, for example, [3]-[5]). Alternately, power grasps can be used, which are typically considered to be safer and more robust to uncertainty [1]. Often, however, grasping is just the first step to a multi-step manipulation process. Manipulation requires dexterous, precision grips that are not well suited to underactuated hands or power grasping. In manipulation planning it is important to have a good object model so that appropriate finger gait and force control can be applied to ensure that the object achieves the desired motion [1], [2]. It is therefore advocated that determining an object model is important for tasks beyond simply lifting and immobilizing an object in a gripper.

Object exploration is a strategy that has been proposed for obtaining friction information (see, for example, [6], [7]) and for developing long-term grasp planning strategies [8], [9], however these strategies tend to be based on visualcues and complex sensory suites and require large datasets to obtain object information.

Some works have been proposed in which reacting to uncertainty and object configuration without knowledge of object properties enables grasping to take place [10]-[13]. We advocate that this approach is helpful when a grasp must be carried out immediately and when time for experimentation is not available. However, for precision manipulation, a method by which object parameters can be obtained is necessary. Through multiple object interactions a robot could build an object model and begin to rely less on reactive methods, with the eventual goal of being able to plan complex manipulation tasks.

Some researchers have developed work dealing with precision grasp and object position control [14]-[16]. Typically, these works require the robot to apply forces in response to object motion and parameters. Central to these works is the knowledge of object COM, which the authors assumed was available. Furthermore, many grasp planning algorithms function by analyzing the object's surface geometry and searching for stable/optimal grasps. These algorithms can find robust contact positions but rely entirely on the knowledge of COM [17]. We advocate exploring the object to obtain this information, which can enable approaches that require this information to move forward for unfamiliar objects.

In this work we propose an object exploration strategy for extracting COM and mass location of an object. Our strategy uses a single interaction episode with the object and does not require visual sensing of the object. The strategy uses only load force and torque sensing and uses only a single six Degree of Freedom (DOF) force/torque sensor mounted on the robot. This work can be used to help develop an object model for further grasp planning/manipulation.

II. Proposed Approach

A. Mathematical Preliminaries

We denote coordinate frames centered at a point P as F_P . A coordinate frame is comprised of a location $P=[x,y,z]$ and a set of orientation angles $\Theta=[\theta,\phi,\mu]$ specified around some convenient axes of rotation that determine the orientation of the frame's 3 axes with respect to the world coordinate frame. The

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world frame is assumed to be centered at the origin [0,0,0] and to have rotation angles of 0. To transform a point from one coordinate frame centered at P_1 to another frame centered at P_2, we use a homogeneous transformation matrix defined as $T = \begin{bmatrix} R & P \\ 0 & 1 \end{bmatrix}$.

A *wrench* $W = \begin{bmatrix} f & \tau \end{bmatrix}^T$ is defined as a six-dimensional vector comprised of 3 forces $f = \begin{bmatrix} f_x, f_y, f_z \end{bmatrix}$ and 3 torques $\tau = \begin{bmatrix} \tau_x, \tau_y, \tau_z \end{bmatrix}$, where the vectors are represented in a particular coordinate frame and the components of those vectors are reckoned with respect to the axes of that frame.

Finally, for mathematical convenience we represent the cross product matrix of a vector $v = [x, y, z]$ as $v^X = \begin{bmatrix} 0 & -z & y \\ z & 0 & -x \\ -y & x & 0 \end{bmatrix}$. The cross product matrix is used in subsequent developments below.

B. Derivation of Proposed Algorithm

COM location can be obtained using a load force/torque sensor provided that the robot is able to grasp the object and immobilize it against gravity. Practically, one can imagine a scenario in which the robot executes a safe power grasp, observes COM and mass, replaces the object and plans a precision grasp after this exploration is complete. The remainder of this section will describe the process by which a single grasp attempt can be used to discern COM and mass.

To begin, consider a coordinate frame centered at the COM denoted F_{COM}, located at some position P_{COM} and rotated by some rotation R_{COM} with respect to the a convenient coordinate frame. In particular, we will be interested in determining the configuration of F_{COM} in the robot's palm frame F_p, and will assume that the transformation between the palm frame and the world frame is known (so that finding the COM location in the palm frame allows us to immediately find it in the world frame as well). It is necessary to determine six unknowns in order to exactly specify F_{COM} in the palm frame - three rotation angles and the three spatial coordinates that make up the components of P_{COM}. Note, however, that the rotation angles can be specified arbitrarily. The object may have a natural orientation for its coordinate axes, but since this cannot be relied upon, a convenient orientation can be chosen *a priori*. To begin, we assume that, prior to the grasp attempt, the frames F_{COM} and F_W are aligned and thus R_{COM} is the identity. As a result, there are, in fact, only three free parameters to be specified: the three spatial coordinates.

Without loss of generality, assume that the load force/torque sensor is attached at the robot's palm frame and aligned with it. Thus we can treat the sensor frame and the palm frame as the same coordinate frame. Furthermore, we assume that initially the palm frame and world frame are aligned. The setup is shown in a simplified 2D representation in Fig. 1 below. Note that, since the object will be in a grasp, there will also be contact frames (shown in Fig. 1), although the exact configuration of these frames is not necessary for the remainder of the developments.

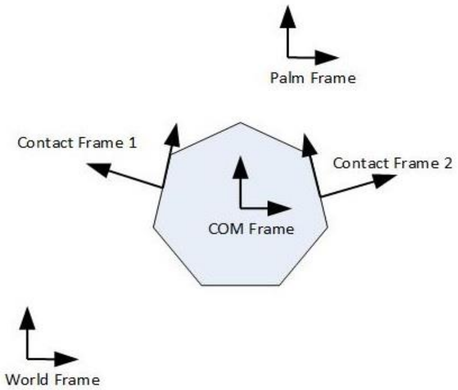

Figure 1. Coordinate frames

From the assumption that the object is immobilized against gravity, we know that the wrench (vector of forces and torques) acting on the COM due to external influences is due only to gravity. Without loss of generality, assume that gravity acts along the –z direction of the world frame, the external wrench acting on the object is

$$W_E = \begin{bmatrix} f_E & \tau_E \end{bmatrix}^T = \begin{bmatrix} 0\,0 - mg\;0\,0\,0 \end{bmatrix}^T \tag{1}$$

where f_E is the 3x1 force vector, τ_E is the 3x1 torque vector, *m* is the object mass and *g* is the acceleration due to gravity.

The procedure takes two steps: first, the load wrench is extracted from the sensor based on the initial grasp. Then, the wrist will be rotated slightly, a second load wrench will be processed, and the exploration will be complete. For simplicity the object will be assumed to be in a top grasp initially. From [1], the wrench measured at the sensor is given by:

$$W_E = \begin{bmatrix} R_{COM} & 0 \\ -P_{COM}^X R_{COM} & R_{COM} \end{bmatrix} W_E + W_{HAND} \tag{2}$$

where P_{COM}^X is the cross product matrix generated by P_{COM} and W_{HAND} is the wrench due to the hand itself - since the hand is configured in space and has nonzero mass, this additional wrench will be sensed during the grasp. For the remainder of this discussion it will be assumed this wrench is either known or can be sensed before the grasp takes place and thus can be subtracted from the sensor readings. As a result, it will be ignored in further discussion.

Note that the forces measured by the sensor rely only on the forces acting on the COM of the object, rotated suitably through the known rotation matrix. This information will be sensed and stored in a vector f_p. Since it is initially assumed that the COM frame and the palm frame are aligned, the sensed forces will be:

$$f_p = f_E \tag{3}$$

Therefore, the object mass can be obtained directly as $m = -\frac{f_{p,z}}{g}$, where $f_{p,z}$ denotes the *z* component of the sensed force.

Now consider the sensed torques, τ_P. Note that since there are no external torques acting on the object the torque sensed is given by:

$$\tau_P = -P_{COM}^{x} R_{COM} f_E \tag{4}$$

If this matrix multiplication is carried out and the matrix is re-arranged, the equation becomes:

$$-\frac{\tau_P}{mg} = \begin{bmatrix} o & -r_{3,3} & r_{2,3} \\ r_{3,3} & 0 & -r_{1,3} \\ -r_{2,3} & r_{1,3} & 0 \end{bmatrix} \begin{bmatrix} P_{COM,X} \\ P_{COM,Y} \\ P_{COM,Z} \end{bmatrix} \tag{5}$$

where $r_{i,j}$ is the entry in the r^{th} row and j^{th} column of R_{COM}.

When the initial grasp is a top grasp (and the frames are oriented as described above), we can substitute the actual entries of R_{COM} to get the equation:

$$-\frac{\tau_P}{mg} = \begin{bmatrix} 0 & -1 & 0 \\ 1 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} P_{COM,X} \\ P_{COM,Y} \\ P_{COM,Z} \end{bmatrix} \tag{6}$$

From this equation we can see immediately that *x* and *y* components are given as:

$$P_{COM,X} = -\frac{\tau_{P,Y}}{mg} \tag{7}$$

and

$$P_{COM,Y} = \frac{\tau_{P,X}}{mg} \tag{8}$$

and unfortunately the *z* component of the COM location cannot be obtained. In general, Equation 5 is always underdetermined since the matrix composed of the entries R_{COM} is always noninvertible. This means that the relative orientation between the COM and palm frames is not relevant - no grasp configuration would result in an equation in which all three unknowns are obtainable from a single grasp. In particular, the matrix has a rank of 2 and therefore at most two of the entries in the COM position vector can be obtained from a single measurement. This is the motivation for the second step in the derivation. This second step is dependent on the original grasp being a top grasp. If this is not the case, a similar derivation can be done. However, for simplicity the top-grasp will be assumed.

With the object already in the hand, rotate the wrist by some angle θ about either the *x* or the *y* axis. This puts the palm frame out of alignment with the world frame but, importantly, keeps the COM frame and the palm frame aligned. Thus, the forces and torques sensed by the sensor will be different after the rotation.

Consider now that, in general, the torque τ induced by a force f acting along a moment arm P is given by:

$$\tau = f \times P \tag{9}$$

where x indicates the vector cross product. In the case of the unknown object COM location, we have that $P = P_{COM}$, $\tau = \tau_P$ is the vector of forces sensed at the wrist, and $f = f_E$ is the vector of forces sensed by the load sensor. By carrying out the cross product we obtain:

$$\tau_P = \begin{bmatrix} f_Z P_{COM,Y} - f_Y P_{COM,Z} \\ f_X P_{COM,Z} - f_Z P_{COM,X} \\ f_Y P_{COM,X} - f_X P_{COM,Y} \end{bmatrix} \tag{10}$$

The unknown $P_{COM,Z}$ is then given by:

$$P_{COM,Z} = \frac{\tau_x - f_Z P_{COM,Y}}{f_r} \tag{11}$$

From the above analysis it can be seen that obtaining the COM location requires only the ability to sense load wrenches at one location, and can take place within a single grasp attempt. A natural question to ask is: by what angle, θ, should the hand be rotated? We will show in the analysis that this angle is involved in the algorithm's sensitivity to noise and object reconfiguration, and thus a tradeoff must be made according to the specific setup that is being used.

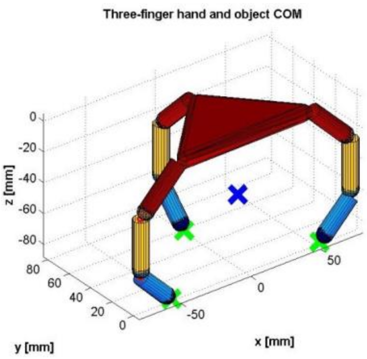

Figure 2. Typical simulation setup

III. Simulation Setup

The above algorithm was simulated in the open-source MATLAB toolbox SynGrasp. A pre-made three-fingered hand was used for the simulation, and all three fingers were placed in contact about an object that was defined to have a mass of 0.1Kg. Fig. 2 shows the simulation setup for a typical simulation run. The contact points are attached to the fingertips only and are shown in green. The actual object COM is shown in blue.

The simulation proceeds as follows. First, the fingers are placed in their contact configuration and the net wrench acting on the object COM during the grasp is evaluated. In order for the object to be immobilized this should be zero however, since the COM location is varied randomly this may not be the case. If the net wrench is zero, the simulation proceeds, otherwise a new COM location is computed. The sensor reading is then simulated for the initial grasp configuration and from this the object mass, along with $P_{COM,X}$ and $P_{COM,Y}$ are extracted. Next, the wrist is rotated about the x axis by some angle. The new sensed wrench is computed after the re-orientation, and from this $P_{COM,Z}$ is extracted.

Three sets of simulations were performed. First, the strategy was tested under the assumption that perfect information was available. In particular, sensor noise and object reconfiguration were not considered. The COM was varied for twenty experiments and the average distance between the computed and actual COM locations was recorded. Second, the effects of sensor noise were simulated and the simulations were re-run. Finally, the effects of object reconfiguration were simulated. In particular, it was assumed that the rotation of the hand caused a displacement in actual COM location by a random value. Since the computation of the *z* coordinate relies on a fixed *x* and *y*, this allowed us to determine the effects of object reconfiguration. For both the second and third experiment set the COM was initialized to the same value so that the desired effect could be studied in isolation.

IV. Simulation Results

A. Case 1: Perfect Information

In this case the COM extraction performed deterministically and the COM location was calculated to within machine precision. The average error between actual and computed COM location was 1.1088e-013, indicating that the algorithm is effective when the effects of noise and reconfiguration are minimized.

For these simulations, a relatively small rotation of $\theta = 0.05 rad$ was used. Ostensibly, choosing the smallest possible rotation angle may be prudent, since it is not guaranteed that tipping the object will not cause undesired reconfiguration. However, we will see below that small angles can lead to unacceptable errors when noise and reconfiguration are introduced.

B. Case 2: Effects of Sensor Noise

Noise was simulated as a Gaussian white noise process with varying standard deviations (shown below). In this case, it was found that, for small angles θ the variation in *z* component determination was greatest. Intuitively this makes sense – for small angles, the relative contribution of the *z* component to the torques acting on the sensor is lower and thus high noise may entirely corrupt this subtle effect. Fig. 3 shows the distribution of COM locations determined over 20 simulations. The standard deviation of the noise for the force was 0.1N and for the torques was 0.1Nm. The rotation angle was $\theta = 0.05 rad$. Note that the magnitude of the force acting on the object was approximately 1N, which may help explain the large variance. The red points indicate computed COM location and the blue X indicates actual COM location.

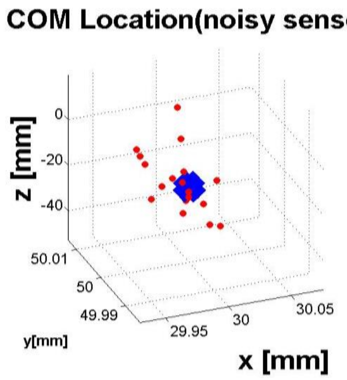

Figure 3. COM location variance due to noise

The rotation angle θ was then changed to $\frac{\pi}{6}$ and $\frac{\pi}{3}$ radians. Histograms of the computed *z* components are shown in Fig. 4 and Fig. 5 for the different angles. Note how, when the angle is larger, the contribution of the *z* component is larger and thus the determination of the *z* coordinate is more precise.

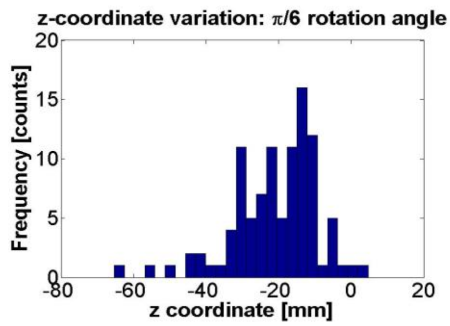

Figure 4. Increasing rotation angle

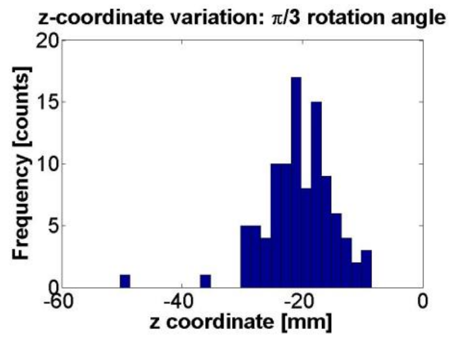

Figure 5. Increasing rotation angle

Table I below shows the standard deviations in the determination of the *x*, *y*, and *z* components of the COM as a function of varying the rotation angle and also the noise standard deviation. As expected, the larger rotation angles produce lower standard deviation and, interestingly, if the noise standard deviation is high enough the calculation can be preposterously incorrect for small rotation angles. Thus a key takeaway is that one should use low noise sensors or good signal processing before proceeding with this strategy. The angle is expressed in radians and standard deviation in mm.

TABLE I. NOISE AND ROTATION ANGLE

θ	σ_{noise}	σ_X	σ_Y	σ_Z
0.05	0.01	0.0102	0.0109	12.86
$\frac{\pi}{6}$	0.01	0.0105	0.0089	0.9785
$\frac{\pi}{3}$	0.01	0.0112	0.0097	0.6331
0.05	0.1	0.1048	0.1092	810.0087
$\frac{\pi}{6}$	0.1	0.1151	0.0988	11.3458
$\frac{\pi}{3}$	0.1	0.0947	0.1038	6.5022

TABLE II. COM VARIATION DUE TO OBJECT RECONFIGURATION

θ	σ_{COM}	σ_Z
0.05	0.1	2.0073
$\frac{\pi}{6}$	0.1	0.1548
$\frac{\pi}{3}$	0.1	0.0523
0.05	10	180.5769
$\frac{\pi}{6}$	10	17.5137
$\frac{\pi}{3}$	10	5.6429
0.05	30	624.5318
$\frac{\pi}{6}$	30	53.4869
$\frac{\pi}{3}$	30	17.3761

C. Case 3: Object Reconfiguration

In this case, it was assumed that the COM location randomly moves after the tipping takes place. The random motion was simulated using a normal distribution with varying standard deviation in mm and mean 0. Table II shows the variance in calculatoin of the *z* coordinate as a function of the standard deviation of the random reconfiguration and the rotation angle θ.

V. SUMMARY AND FUTURE WORK

In this paper we have developed a strategy for determination of object COM location and mass for robot grasping. The strategy requires the robot to execute a test grasp on the object and interact with it by measuring induced load forces and torques. The algorithm was tested in simulation and it was found that submillimeter determination precision is possible for some noise bounds. This strategy can be used as part of a multi-step object exploration system for determining important object parameters for eventual use in precision grasping and manipulation tasks. Since it requires only a 6 DOF force/torque sensor it is relatively easy to implement and may be deployed on many common robot platforms.

It was shown that a larger rotation angle during exploration can significantly improve precision. Although it seems that a good strategy would be to increase the rotation angle in order to increase robustness to both noise and object reconfiguration, this may be impossible for some objects (tipping a full mug of water is ill advised, for instance), or it may cause permanent reconfiguration. Thus, a good strategy would be to reduce the noise level in the sensors as much as possible and to only rotate by as small an angle as necessary to achieve acceptable results. This may require the operator to tune the parameters of the algorithm to suit their particular setup.

In the future we intend to test these simulation results on a physical system and investigate the effects of object shape and mass.

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