Robotic Grasping and Manipulation Controller Framework
Architecture Redevelopment

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Abstract: This paper details the further improvements obtained by redesigning a previously offered Manipulation Controller Framework to provide support to an innovative, friction-based object slippage detection strategy employed by the robotic object manipulator. This upgraded Manipulation Controller Framework includes improved slippage detection functionality and a streamlined architecture designed to improve controller robustness, reliability and speed. Improvements include enhancements to object slippage detection strategy, the removal of the decision making module and integration of its functionality into the Motion Planner, and the stream-lining of the Motion Planner to improve its effectiveness. It is anticipated that this work will be useful to researchers developing integrated robot controller architectures and slippage control.

1 INTRODUCTION

This paper presents an improved robotic Manipulation Controller Framework architecture (Figure 1) that was offered in an earlier paper (Dzitac and Mazid, 2012).

Literature survey revealed that various framework architectures have been proposed by other researchers. Khalil and Payeur, 2007, proposed and integrated framework based on earlier work by Howard and Bekey, 2000. This framework is intended to facilitate interaction with deformable objects under robot vision and tactile sensing guidance. Prats et al, 2009, proposed a control framework for vision-tactile force and physical robot interaction. Wettels et al, 2009, proposed a grasp control algorithm that uses a Kalman filter to provide a robust tangential force feedback signal from the gripper during object manipulation.

These are just some of the object manipulation control frameworks and algorithms proposed by researchers that strive to develop architectures with ever better functionality and effectiveness.

The controller framework presented in this paper is not an attempt to develop the ideal framework, but rather to improve the performance and usefulness of the proposed framework architecture, and hopefully contribute with a good idea to the research effort in this area of robotics.

The highest priority task in this project has been to improve the effectiveness of the slippage detection and slippage prevention function. This has been achieved mainly by redeveloping the sensor fusion function to help enhance the effectiveness of the slippage detection strategy. Overall, this resulted in an improved ability to predict slippage, and also to differentiate between small and large slippages.

The decision making module has been merged into the motion planning module, and therefore unnecessary redundancy and complexity has been eliminated.

The control module interactions that were not adding value to controller performance have also been discarded.

2 MANIPULATION CONTROLLER FRAMEWORK

The most challenging part of developing the robotic manipulation controller framework for this project has been found to be the development of an effective and streamlined architecture that eliminates unnecessary control functions, data processing and interaction redundancies, but at the same time provides the essential information and interactions to ensure fast and effective control.

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Based on authors' experience gained during experimentation with various versions of the controller framework, it can be stated that the manipulation controller framework architecture plays the most important role in the ability of the controller to perform object grasping and manipulation tasks.

In general, the various control functions can be readily modified, especially when their output has no significant impact on other functions. The controller architecture, on the other hand, defines the hierarchies of control functions and their interactions at system level; it is the "strategic and tactical manager" of the controller. Get this wrong and the controller will be close to useless. This is why researchers invest significant effort into the development of robust controller architectures that incorporate the necessary functionality for safe and reliable robotic object grasping and manipulation.

This controller framework architecture has been developed in the following sequence:

a. Establish the final control capabilities that the controller needs, such as the Motion Path that the robot has to follow, motion Speed and arm joint Force necessary for robot movement;
b. Establish the major inputs needed to provide the necessary data (such as Grasp Data and Object Data) required to achieve these control tasks;
c. Establish the sources of this data, such as Decision Engine and Slippage Detection functions;
d. Group the data sources into major functions, such as Motion Planner and Motion Controller to remove unnecessary detail and simplify the interactions between major controller modules;
e. Establish feedback loops for functions that require feedback for reasonable decision making;
f. Determine the physical sensors needed to provide the required data on which decisions are going to be based;
g. Rationalise the data sources, streamline the interactions between functions and simplify the framework to improve robustness.

In order to facilitate understanding of the overall object grasping and manipulation approach, the robotic manipulation controller framework and its functional modules (Figure 1), including the Sensing Processor, the Instinctive Controller, the Motion Planner and the Motion Controller are presented using figures and short descriptions. The slippage sensing approach used is presented in more detail.

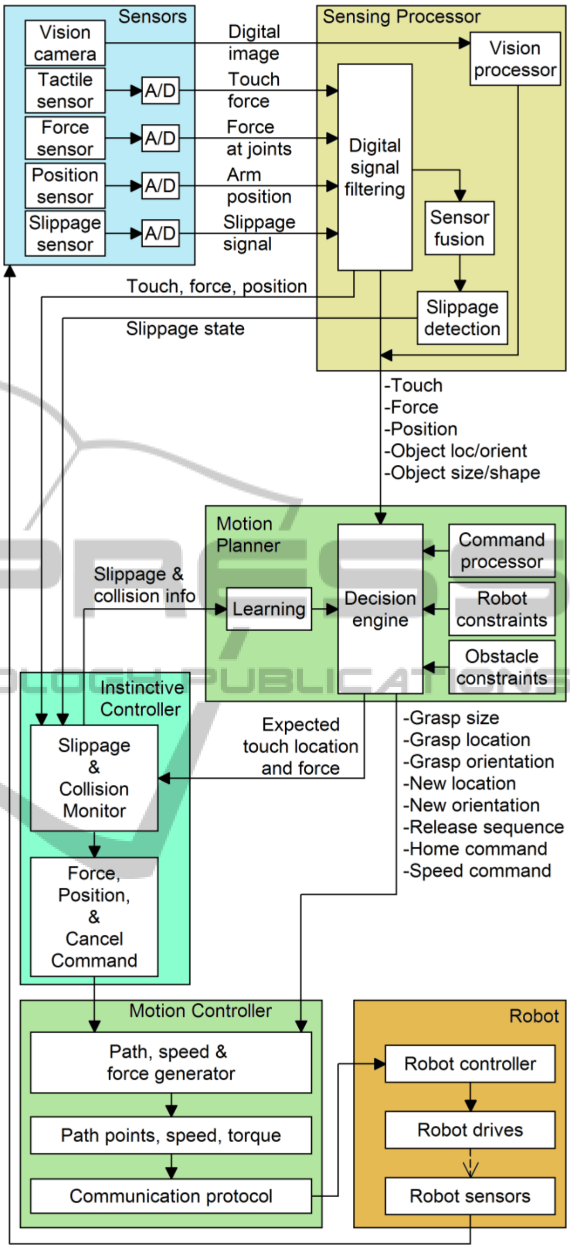


Figure 1: The proposed grasp and manipulation controller framework.

The "Sensors" used in the manipulation controller framework are a digital camera used for object detection, tactile forces (grasp force from gripper motor current and tangential force from gripper shaft torque), arm joint force sensing (from joint motor current), arm position and an innovative friction-based slippage sensor.

The "Robot" is a typical robot capable of accepting and executing motion commands.

2.1 Sensing Processor

The Sensing Processor module (Refer to Figure 1) is based on mathematical and logic control models designed to:

a. Process the vision feedback and convert it into object location, orientation, size and shape information;
b. Use digital filtering to filter the digitized sensor signals and convert them into stable feedback signals required by the control modules;
c. Use sensor fusion at system level to improve slippage detection reliability and enhance slippage information detail.

The vision feedback has been implemented at basic level that is sufficient to allow the controller to detect the object, determine its location, orientation and size, and plan the motion necessary to grasp and relocate the object to a new location.

Digital filtering used is based on a running average of 21 values similar to that presented by Smith, 1999.

Sensor fusion has been implemented at system level and designed to support the slippage detection function within the sensing processor module.

2.1.1 Sensor Fusion for Slippage Detection

Initially sensor fusion for slippage detection has been based on the tangential force sensor and vision feedback. However this proved to be difficult due to the need for complex, real time object position feedback from the slow vision camera.

The current sensor fusion (Figure 2) is based on feedback from a slippage sensor and a tangential force sensor. The slippage sensor used has an inherent slippage detection capability, rather than derived slippage detection based on micro-vibration. The tangential force sensing is based on the torque developed by the manipulated object on the gripper's roller-shaft pair (Dzitac and Mazid, 2012).

A major advantage of this redeveloped slippage detection strategy is the ability to provide detailed slippage information including "potential" slippage and slippage magnitude.

Potential slippage is defined here as slippage that has not yet been detected by the dedicated slippage sensor, however based on tangential force changes relative to the current grasp force, slippage is about to occur because there is barely any grasp force safety margin left.

The grasp force safety margin threshold level has been based on the estimated static coefficient of friction at the gripper-object interface. The grasp force safety margin is adjusted during object manipulation based on feedback from the dedicated slippage sensor.

In this controller the magnitude of the grasp force safety margin F_{SM} is estimated as

$$F_{SM} = \mu_s F - F_t \qquad (1)$$

where F is the grasp force, F_t is the tangential force on the gripper (force that tends to slide the object out of the gripper) developped by the mass of the manipulated object when no slippage takes place, and the static coefficient of friction μ_s is estimated as

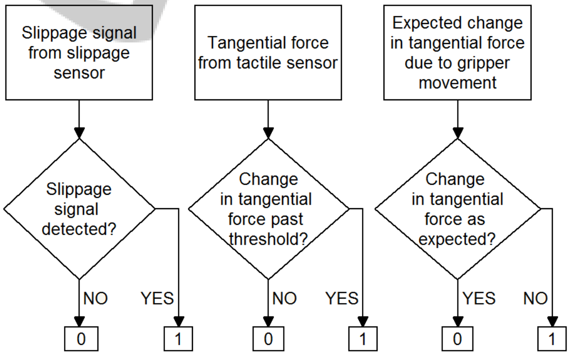
$$\mu_s = F_{start} / F_{stop} \qquad (2)$$

where F_{start} is the grasp force value at the point of impending slippage and F_{stop} is the grasp force value at the point where slippage stops. The slippage start and stop points are provided by the dedicated slippage sensor during object manipulation.

The minimum grasp force safety margin F_{SM} in this controller is limited such that

$$0.05\, F_t < F_{SM} < 0.15\, F_t \qquad (3)$$

Equation 1 allows the controller to adjust the grasp force safety margin within the limits of equatiom 3 in order to prevent slippage and avoid excessive grasp forces.



Truth table			
0	0	0	No slippage
0	0	1	No slippage
0	1	0	No slippage
0	1	1	Potential slippage detected
1	0	1	Small slippage detected
1	1	0	Small slippage detected
1	1	1	Large slippage detected

Figure 2: Sensor fusion for slippage detection.

2.2 Instinctive Controller

The Instinctive Controller module (Figure 3) is a type of reactive controller that has been designed to:

a. Bypass the slow control actions of Motion Planner, and therefore generate fast, instinctlike reactions to unintended touch, collision and slippage in order to prevent damage to robot hardware and the manipulated object;

b. Provide collision and slippage feedback to the Motion Planning module to help improve its performance.

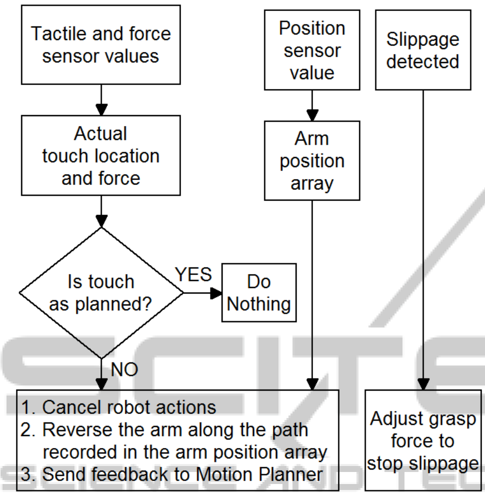


Figure 3: Instinctive Controller algorithm structure.

2.3 Motion Planner

The decision making module employed in the previous version of the manipulation controller framework (Dzitac and Mazid, 2012) has now been incorporated into the motion planner in an attempt to eliminate redundancy, reduce controller complexity, and improve its robustness.

The Motion Planning module (Figure 4 and Figure 5) has been designed to determine the actions to be taken based on a novel target object selected by user, of which the controller has no prior knowledge. When user selects the target object and the new desired object location, the planner performs the following tasks:

a. Decides whether the target object can be grasped based on object info and obstacle info obtained from vision camera.

b. Decides whether the object can be moved to the new location designated by user.

c. Decides gripper orientation for grasping and releasing the object based on object shape/size/location/orientation and the surounding obstacles.

d. Generates a sequence of grasp and move actions that have to be performed (move to object location, orientate gripper, grasp object, move object to new location, orientate object, release object, go home).

e. Generates force and speed constraints for the grasp and move actions based on object data.

f. Passes the generated information to the Motion Controller module.

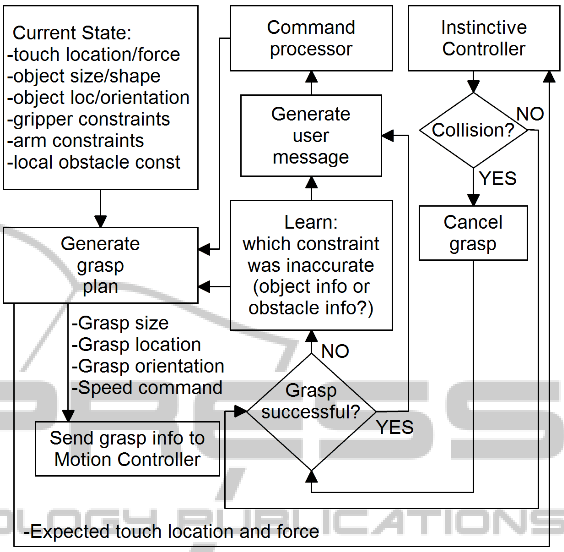


Figure 4: Object grasp planning algorithm structure employed by Motion Planner.

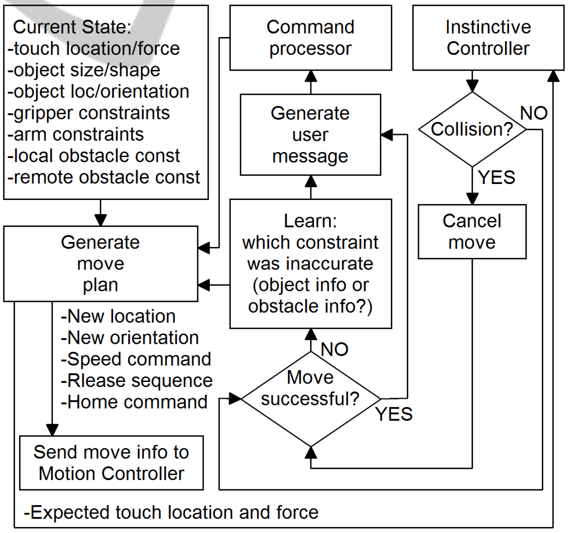


Figure 5: Object move planning algorithm structure employed by Motion Planner.

2.4 Motion Controller

The Motion Controller module (Figure 6) has been designed to:

a. Generate a detailed sequence of motion path points and orientations based on the action sequence generated by the Motion Planning module.

b. Apply speed/acceleration and force constraints.

c. Feed the target position points, gripper orientation and grasp actions at the appropriate time to the robot controller that performs the actual control of the robot.

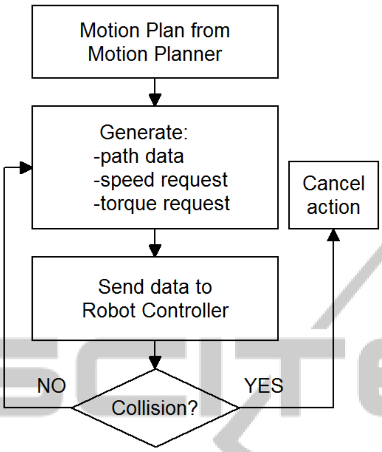


Figure 6: Motion Control algorithm structure.

2.5 Robot Gripper and Arm Controller

The Robot consists of hardware and firmware that responds to instructions received from the Motion Controller and converts them to robot actions.

The robot is capable of accepting path data (position coordinates and orientation), speed, acceleration and torque commands, and executing movement sequences according to this information.

Figure 7 depicts the experimental setup using a basic XYZ+R robot equipped with an object detection camera, friction-based slippage detection gripper and a custom robot controller capable of accepting and executing control commands from the manipulation controller framework running on a PC.

The robot has four degrees of freedom and, apart from being capable of movement in Cartesian coordinates, it can rotate the gripper around its vertical axis. This allows the robot to move to the object position coordinates provided by the vision function and rotate the gripper based on the object orientation in the horizontal plane.

Although not very flexible, the robot can execute object grasping and motion sequences that are sufficient for carrying out any relevant object grasping, manipulation and slippage detection experiments.

The hardware for sensor signal digitising is located in the robot controller. Currently the digital filtering task is performed on the PC by the Sensing Processor module. However, due to the need for real time processing, it would be preferable to digitise and filter the signals remotely before sending these signals to the control PC.

Figure 7: Experimental setup for executing object grasping and manipulation tasks.

Figure 8 describes schematically the experimental setup of Figure 7. Note that the gripper “jaws” (i.e. rollers on shafts) are also the slippage and tangential force sensing elements. This gripper allows reliable slippage and tangential force measurement in one axis. The working principle of this slippage sensing strategy is detailed in an earlier paper (Dzitac and Mazid, 2012).

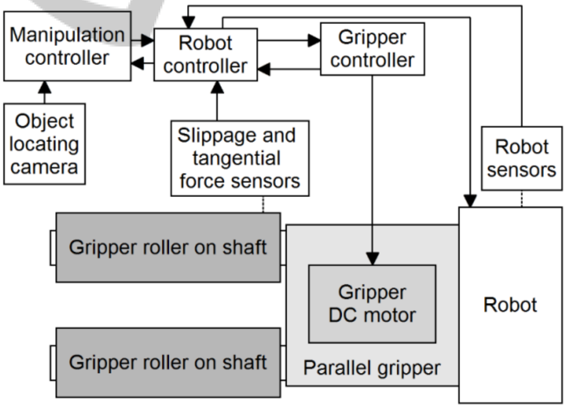


Figure 8: Schematic of the experimental setup for executing object grasping and manipulation tasks.

3 EXPERIMENTATION AND RESULTS

Object grasping and manipulation experimentation has been conducted with the redeveloped manipulation controller framework and slippage sensing function to determine its ability to control object slippage reliably.

The object manipulation has been conducted using a custom parallel gripper capable of sensing grasp force, and also tangential force and slippage in the vertical direction. A rectangular aluminium object of 100x50x22mm and weighing approximately 300 grams has been grasped, lifted vertically and moved to a new location at a maximum acceleration of 100mm/sec and a maximum speed of 300mm/sec.

The experiments conducted demonstrate that using sensor fusion to monitor proximity to slippage and using equations 1 and 3 to adjust grasp force safety margin allows the controller to predict and prevent object slippage more reliably.

A summary of the experimentation results is presented in Table 1. All object manipulation attempts were performed on the same object, using the same acceleration, velocity and deceleration for all manipulation attempts.

As a result of replacing the slow vision feedback used in the previous version of the sensor fusion function with tangential force feedback, the improved slippage detection function gained slippage detection speed and the ability to predict proximity to slippage. In most circumstances the vision feedback was either to slow or unconvincing. The overall performance gain is evident from the Table 1 results.

Table 1: Slippage prevention ability comparison of previous and current slippage detection methods when manipulating a novel object.

Number of object lifting attempts	Unpredicted slippage using previous method	Unpredicted slippage using current method
10	6	1

4 CONCLUSIONS

This paper presented the redevelopped manipulation controller framework and the additional benefits that the elimination of unnecessary control functions, data processing and interaction redundancies bring to safe and reliable object grasping and manipulation. In particular the sensor fusion function enhancements and the use of equations 1 and 3 to control grasp force safety margin resulted in improved controller ability to predict, detect and control object slippage in the robot gripper.

A practical method of estimating the static coefficient of friction (using equation 2) during object manipulation based on feedback from the grasp force sensor and slippage sensor was presented.

The manipulation controller framework presented here could be used equally well with Cartesian and articulated robots, because the motion controller provides the target coordinates, force and speed information, while the robot controller tells the robot how to get there. This means that the manipulation controller framework can work with any robot controller that understands the motion, force and speed commands received from the motion controller module.

It is envisaged that this work will be useful to researchers developing object manipulation controller frameworks and slippage detection and control strategies.

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