Modelling of a Grasping and Manipulation Controller

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Abstract: This paper presents the development of a robot grasping and manipulation control system, including the modelling approach for the control functions, and the criteria used for functional module design in order to achieve the required functionality and allow its integration into the overall control model. This work is an example of a practical implementation of a robotic grasping and manipulation controller and may be relevant to researchers looking for an example of a practical controller design "from scratch".

1 INTRODUCTION

This paper presents the detailed architecture modelling of a controller for a robotic object manipulator, as part of a project that aims to develop reliable and safe object manipulation as its main attributes. The controller architecture is designed to use tactile, force, position and vision sensing. It also makes use of sensor fusion and learning concepts to improve controller performance through robust feedback and "intelligent" decisions.

The concept of instinctive control, for the purpose of fast reactions to unexpected events such as collisions or unexpected object slippage, is also included in the controller architecture.

2 LITERATURE REVIEW

Significant amount of work has already been done by researcher to develop robot control strategies that would maximise the capability of individual sensing technologies through their strategic integration. (Namiki and Ishikawa, 1996), (Allen et al., 1999), (Boshra and Zhang, 2000), and (Prats et al., 2009) used sensor fusion strategies to integrate vision and tactile sensing to improve grasping. Pelossof et al (2004) used simulation based on SVM (Support Vector Machine) method to find optimum grasps for complex shape objects. Khalil and Payeur (2007) proposed a control strategy specifically aimed at grasping deformable objects.

A brief description of the proposed control architecture in this paper was given by Dzitac and Mazid (2011). This control architecture is presented here in detail.

3 MODEL DEVELOPMENT

3.1 The Choice of Control Model

The minimum necessary controller functionality is based on the minimum project requirements which are as follows:

1. Find an egg cup that matches the colour of the target egg (chosen by user), and orientate the egg cup correctly.
2. Find an egg that matches the colour of the egg cup and place the egg safely in it.
3. Find a metal bushing and a matching shaft, and insert the shaft into the bushing.
4. Find a thin-walled plastic drink bottle and move it safely to a location designated by the user. The amount water in the bottle not known to the controller.

The first requirement tests the manipulation dexterity of the controller because the egg cup could be sitting upside-down.

The second requirement tests the ability to apply only the absolutely minimum grasping forces to a rigid but fragile object that will fail catastrophically if the allowable grasping force is exceeded.

The third requirement tests the ability to orientate parts correctly and assemble parts with reasonable

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dexterity.

The fourth requirement tests the ability to maintain grasp control of a deformable object without prior knowledge of object characteristics.

3.2 Robot Capabilities

The robot must be able to locate the target objects and potential obstacles in the area and therefore the robot must have the following capabilities:

1. Detect known objects
2. Estimate object location and orientation
3. Estimate object shape
4. Estimate object size
5. Discriminate objects by colour

For reasonable dexterity the robot must also have:

1. Velocity and acceleration control for fingers, hand and arm
2. Position control for fingers, hand and arm
3. Tactile sensing for sensitive touch detection
4. Grip force control for heavier grasp
5. Object slippage detection
6. Sufficient degrees of freedom

3.3 Manipulation Controller Design

The specified object manipulation capability requires a controller with several modules, each with specialized functions to facilitate grasping and slippage control. The block diagram in Figure 1 shows the controller functional modules and their interactions.

The *sensors* selected for robot's tactile, force, position and vision capabilities are considered to be the minimum number of sensors required for successful grasping and manipulation.

The tactile, force and position sensors output an analog voltage of 0 to 5VDC, which is proportional to the sensing range of the respective sensors.

The term "tactile sensor" is used to represent sensitive force sensors with a small sensing range. These sensors are used to detect the instant at which an object is touched and for manipulating small, fragile objects. The term "force sensors" is used to represent sensors with a large force sensing range and lower sensitivity, such as those in the robot arm.

The *Sensing Processor* module is based on a combination of mathematical and logic control models, depending on the specific requirements of each function. The Sensing Processor is designed:

1. To filter the digitized analog sensor signals using digital filters.
2. Use sensor fusion to improve sensor feedback reliability.
3. Convert the sensor feedback into useful information for other controller modules.

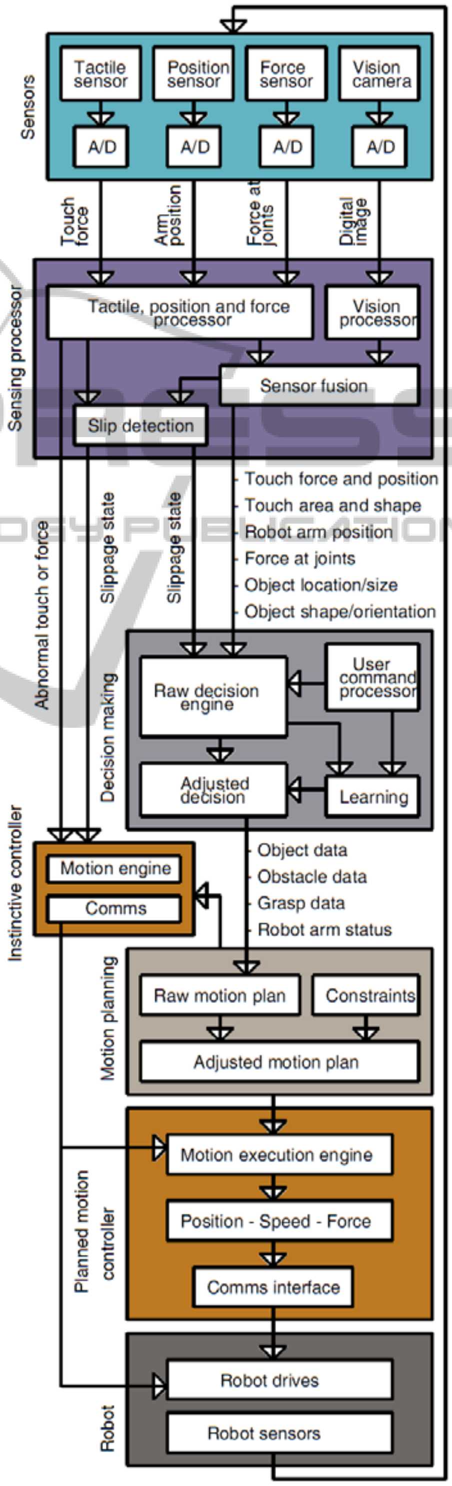

Figure 1: The grasp and manipulation controller.

In order to achieve confident manipulation, grasping force control and slip detection it is important to have quality feedback signals, which translate into two specific requirements:

1. The grasping hardware must be capable of controlling the grasping forces with adequate mechanical resolution and speed.
2. The feedback system must provide accurate information, in real time, to the relevant modules that control the grasping hardware.

Sensor fusion acts as a filter to help produce reliable information. A voting scheme is used. For example the controller must know the position of the robot arm, hand and fingers to determine whether the slippage sensed by the tactile sensors is real.

The *Instinctive Controller* module was designed to:

1. Bypass the slow, planned control flow to generate fast, instinct-like reactions.
2. React to touch, collision and sensory overload
3. Request fast, local reaction from the robot drives.
4. Provide feedback to the Decision-Making module and the robot safety controller.

The basic structure of the Instinctive Controller's logic decision engine is shown in Figure 2. The Instinctive Controller is based on logic control that determines whether the touch and forces sensed by the robot arm are as planned by the Motion Planning module or are abnormal. The instinctive motion controller does not compute a new motion path: it keeps a record of the current motion path, and in case of an abnormal event it reverses the robot arm along the same path for a short distance.

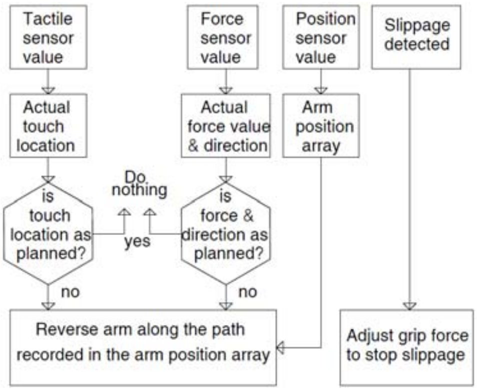

Figure 2: Logic control block diagram of Instinctive Controller.

In order to prevent loss of control, the Instinctive Controller reacts fast to slippage events that were determined by the Sensing Processor and passed to the Instinctive Controller.

The *Decision-Making* module was designed to determine the actions to be taken based on objectives set by the user, sensory information and performance feedback from the learning module. It performs two main tasks: decides whether the object can be grasped, as shown in Figure 3, and whether the object can be moved, as shown in Figure 4.

The grasping function uses feedback from the Sensing Processor that provides information about the target object and all other objects around the target object including:

1. Object size
2. Object shape
3. Object location
4. Object orientation

The Decision-Making module monitors the following information provided by the Sensing Processor during grasping:

1. Tactile info (touch location/area)
2. Force info (force at finger joints)
3. Arm/hand/finger position info

Before initiating a grasping attempt, the Decision-Making module searches for obstacles that would prevent object grasping. An obstacle is any object located around the target object that prevents grasping the target object. If grasp is possible it will forward the following grasp information to the Motion Planning module:

1. Target object info (size / shape / location / orientation)
2. Obstacle info (size / shape / location / orientation)
3. Tactile info
4. Force info
5. Arm / hand / finger position info

This information will be continuously updated during grasping and forwarded to the Motion Planning module until grasping is complete. If an abnormal event takes place, such as an unexpected collision, the Decision-Making module will abort the grasping attempt. The grasp abortion criteria are the same as that used by the Instinctive Controller. The recovery sequence retracts the robot arm to a safe position and then tries again.

The Learning function will "remember" which constraint was violated and why, and will provide this information to the Decision-Making module during the next grasping attempt to help prevent the same estimation error.

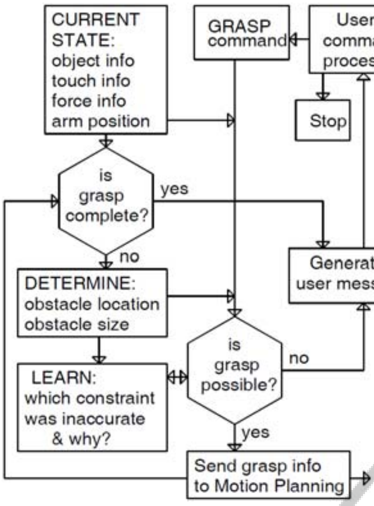

Figure 3: Object grasping algorithm structure.

The object move (relocation) function uses feedback from the Sensing Processor that provides the following information during object move:

1. Target object info
2. Tactile info
3. Force at fingers, hand and arm joints
4. Arm/hand/finger position info
5. Object slippage info

The object move function also uses information compiled by the Decision-Making module which includes:

1. Local obstacle info
2. Remote location info (where object will be placed)
3. Remote obstacle info

The Decision-Making module determines whether there are obstacles that would prevent moving the object to its new destination. If there is sufficient distance between the obstacle and the target object to allow the object to be moved, the Decision-Making module will decide that the move is possible and will forward the following object move information to the Motion Planning module:

1. Target object info
2. Remote location info
3. Local and remote obstacle info
4. Tactile info
5. Force at fingers, hand and arm joints
6. Arm/hand/finger position info
7. Object slippage info

This information will be continuously updated during object move and forwarded to the Motion Planning module until object move is complete. If an abnormal event takes place, such as unexpected collision, the Decision-Making module will abort the move attempt. The object move abortion criteria are the same as that used by the Instinctive Controller. The recovery sequence retracts the robot arm to a safe position and then tries again.

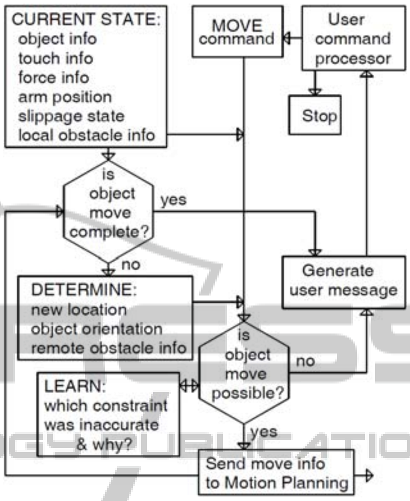

Figure 4: Object moving algorithm structure.

The Learning function will "remember" which constraint was violated and why. It will provide this information to the Decision-Making module during the next object move attempt to help prevent the same estimation error.

The *Motion Planning* module was designed to plan the grasping and the motion of the robot arm based on action requests received from the Decision-Making module. This module uses rule-based grasp planning as shown in Figure 5.

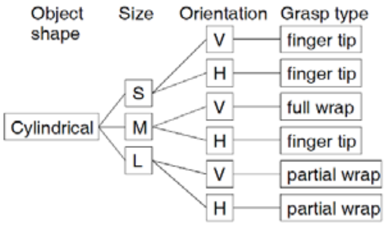

Figure 5: Grasp rule for cylindrical objects.

The *Planned Motion Controller* (planned motion trajectory generator) was designed to execute the motion plan generated by the Motion Planning module. It generates a sequence of motion path points based on the motion path generated by the Motion Planning module and velocity constraints, and feeds these points at the correct time to the robot drives that perform the actual position control of the servo motors.

The *Robot hand and arm controller* module consists of the hardware and firmware that executes robot hand and arm actions, and responds to instructions received from the motion controllers.

3.4 The Vision System

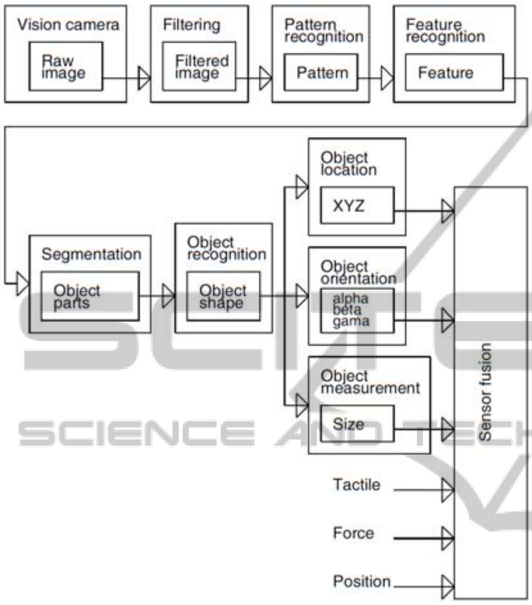

Figure 6: Simplified block diagram of vision system.

To be capable of finding, grasping and manipulating objects the robot must be equipped with a vision system that can perform the vision tasks mentioned in section 3.1. The vision system is not the main research objective in this project, but it is indispensable for an autonomous object grasping and manipulation system.

At this stage the vision system detects simple objects, such as cylinders, eggs and drinks bottles, and estimates their location, orientation and size.

4 IMPLEMENTATION AND RESULTS

An average egg weighs around 50g (~500mN). Experimentation shows that to hold an egg in vertical orientation with a two-finger gripper the grasping mechanism would have to apply a grasp force of about 1N. To achieve reasonable force control during egg grasping the force sensing and control resolution of the grasping mechanism must be capable of a minimum resolution of 1 in 100 (i.e. at least 1N / 100 = 10mN). This is in the sensitivity range of the *tactile* force sensors. For this prototype, the maximum tactile grasping force range of the grasping mechanism has been limited to 5N.

Assuming that the grasping mechanism has sufficient mechanical control resolution, the force sensor signal must be discriminated to 10mN or less. A 9 bit A/D converter would provide 5N / 511 = 9.8mN, which is sufficient resolution for ideal signal quality. However the least significant bit (LSB) of the digitized signal is corrupted by noise, so a better choice is a 12Bit converter because it provides a higher signal resolution (5N / 4095 = 1.2mN), which facilitates noise filtering and signal reconstruction.

The signal reconstruction resolution is dependent on the A/D converter resolution, sampling frequency and the number of samples used per sampling period. The fidelity of the reconstructed signal must be sufficient to provide a good representation of the actual sensor signal, minus the random noise.

A digital signal analyser was used to determine the type of noise in the analog signals coming from sensors. It was determined that the noise was mostly random noise.

The Sensing Processor performs digital signal filtering on the tactile, position and force feedback signals. The model used for digital filtering is based on the recursive moving average filter, which is optimum for eliminating random noise. The filter used is based on a running average (Smith, 1999) of 20 values and its output *y* is given by

$$y[n] = (y\,[n-1] + x[nm+1] - x[nm - (m-1)]]) / 2 \qquad (1)$$

where y[n] is the current point being calculated, *y[n-1]* is the previous calculated point, *x[nm+1]* is the latest sample, *x[nm-(m-1)* is the oldest sample, *n* is the current sample number and *m* is the number of samples in the moving average. Note that y[0] must be initialise by getting *m* number of samples and calculating the average before equation (1) can be used (Smith, 1999).

The control system uses an FPGA, which is interfaced with a 12 bit A/D converter that has a parallel data bus. Each of the 12 bits of the A/D converter is connected in parallel to the FPGA inputs, which allows the digital filters to use higher signal sampling rates if necessary. The 12 bit A/D provides a resolution of 5V / 4095 = 1.22mV.

The tactile sensor outputs 0-5V when it is compressed 1mm. The grasping mechanism can move with a maximum linear velocity of 100mm/s, therefore it takes the sensor output 10ms to change from the minimum of 0V to the maximum of 5V from the point of contact with the object. The sensor DC signal is reconstructed at 100ksps samples.

This gives 100ksps * 0.01s = 1000 signal reconstruction points during the 10ms when the sensor signal changes from 0 to 5V. This is equivalent to 5N / 1000 = 5mN tactile grasping force resolution. Note that during the fastest sensor signal change rate, the control system can only distinguish the grasping force at a resolution of 5mN despite the fact that the A/D converter can provide a resolution of 1.2mN.

To allow the prototype to manipulate heavier objects, such as the plastic drink bottle described earlier, the “bulk” grasping force sensing was designed for a maximum of 20N.

The same analysis as for the 0-5N range tactile sensor is applicable to the 0-20N range force sensor. A 12 bit converter was selected, which provides a signal conversion resolution of 20N / 4095 = 4.9mN.

The force sensor outputs 0-5V when the finger is deflected 4mm at the tip (finger has compliant joints). The grasping mechanism can move with a maximum linear velocity of 100mm/s, therefore it takes the sensor output 40ms to change from the minimum of 0V to the maximum of 5V from the point of contact with the object. The sensor DC signal is reconstructed at 100ksps, which gives 100ksps * 0.01s = 1000 signal reconstruction points during the 40ms when the sensor signal changes from 0 to 5V. This is equivalent to 20N / 1000 = 20mN grasping force resolution. During the fastest sensor signal change rate, the control system can only distinguish the grasping force at a resolution of 20mN despite the fact that the A/D converter can provide a resolution of 4.9mN.

The position sensors output 0 to 5V per 90 degrees of rotation. Using a 12 bit A/D converter gives a resolution of 90 deg / 4095 = 0.022 degrees. If a resolution of 0.03 degrees is used, the resolution at the end of a robot arm with two links of 300mm each is 1mm, which is adequate for reliable arm, hand and finger positioning during object manipulation.

Object handling experimentation shows that the choice of sensor signal feedback resolution and update frequency is adequate for reliable control of fragile object grasping and safe manipulation.

5 CONCLUSIONS

The main objective in this project is to develop object grasping and manipulation with collision detection and slippage control to allow the robot to manipulate objects safely with useful dexterity. The most challenging part in the project is to achieve useful feedback information from sensors.

Currently the experimental tactile slippage sensing approach is based on a parallel-jaw gripper that provides acceptable slippage detection but only in one axis (object rotation in the gripper is only detected by vision). Further work is needed to develop a robust slippage sensing strategy that would provide reliable slippage status feedback to help detect and prevent slippage in all axes.

Further work is needed to add advanced functionality to the sensor fusion module. The learning module also needs further work to improve its usefulness.

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