Analysis of Sensor and Gripper Jaw Response Times

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***Abstract*— this paper presents the importance of designing a robotic grasping mechanism from the mechanical resolution and sensing resolution perspective. A low grasping system mechanical resolution defeats the purpose of high sensing resolution. A low sensing resolution capability defeats the purpose of a high mechanical control resolution. In either case the result is inadequate grasping control for precision grasping. An adequate balance is required between sensing and mechanical resolutions to maximize the potential of both. Grasping mechanism's grasp range and sensing range are important as well, because these affect slippage control, precision grasping, and safe object manipulation.**

Keywords—*precision grasping, gripper, sensor, resolution*

I. INTRODUCTION

A simple parallel-jaw gripper with resistive sensors and a force sensor has been designed and the prototype (Fig. 1) has been built for experimental purposes. This prototype gripper has been used to analyse comparative resolution of a mechanical gripper drive and the sensor function. The new gripper uses a stepper motor for actuation of one jaw while the second jaw is rigid and stationary. The stepper-motor has been used as an actuator to test the effect of various actuator resolutions on grasping, while a force sensor has been used to detect the single direction grasping force.

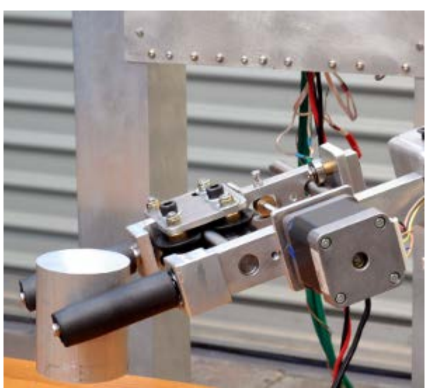

Figure 1. Prototype gripper for testing parrallel gripper contact using compliant and rigid jaws

After encountering many challenges during the design and testing of this grasping mechanism (robot hand) useful information on the importance of grasping mechanism's sensing and resolution of mechanical drive has been complied and analyzed in this paper.

The variation of actuation and sensing resolutions is often overlooked when designing a robotic grasping mechanism, although these deserve a higher design priority than they are typically given for their role in precision and robust applications. Precision grasping is essential for many industrial applications, medical surgery, assembly operations and even for handling brittle and fragile items like eggs, strawberries, etc.

The typical object grasping research project is primarily concerned with the difficult task of finding a sensing technique or mechanical solution to the grasping problem. As literature survey suggests, the sensing and mechanical resolution balance issues are usually the last thing on the researcher's mind. In general, both the mechanical and sensing resolution must be balanced such that one does not reduce the effectiveness of the other for precision grasping.

By mechanical resolution we mean the ability of the actuation device to control the grasping mechanism movement in adequate increments with precision. An example is the stepper-motor actuation version of the prototype grasping mechanism. The resolution is acceptable because the stepper motors can move in micro-steps (e.g. 16 micro-steps per 1.8º full step). However, if they could only move in full-steps of 1.8º, the actuation resolution would be too coarse for high precision grasp control.

The innovative findings of this paper will be useful for those who usually design grasping mechanism for precision grasping and manipulation. The paper presents the necessary analysis that needs to be conducted during design phase in order to achieve an effective balance between the mechanical and sensing resolution. Mechanical grasping range and force sensing range are also discussed in this context to highlight their contribution towards a well designed grasping system for precision applications.

II. ANALYSIS OF REACTION, ACTION AND RESPONSE TIMES

The response time of a device is the shortest time in which the device can respond to a command. The response time can be split into reaction and action times. A distinction can be made between these two components in a similar way to that made by Mackenzie [2] for human response to stimulus. Reaction time can be defined as the elapsed time from the instant when a stimulus (input) is applied to the instant when the action starts. The remaining time of the total response time is the action time.

The current research is aimed at grasping mechanism's stopping performance, to prevent excessive grasp force application to fragile objects. From this perspective, the fastest possible response time of an actuation device to a stop command is the sum of its reaction time and its shortest possible action time.

$$Response\ time = reaction\ time + action\ time \quad (1)$$

Ideal devices have zero reaction time, and their action time is fully controllable (can be made as short as desired). Most real devices used in robotic grasping systems have non-zero reaction times, and their action times have a fixed duration.

Typical response times of real actuators range from nanoseconds to milliseconds. When several such devices are in series (one device triggers the next one) the response times accumulate to an amount that may or may not be acceptable for adequate control. An example is an electric motor-drive combination, as used for robot hand actuation. There is a delay from the instant when a stop command is issued to the drive until the motor begins to slow down, which according to our definition is the reaction time. The action time starts when the motor begins to slow down and ends when the motor is completely stopped. In this case the shortest possible action time depends on the deceleration rate capability of the motor-drive combination.

Typically only the response time is mentioned in technical specifications, because in most cases it is difficult or impractical to clearly separate the reaction and action time. An example is an electromechanical relay where it makes more sense to consider the total response time of the relay rather than separating the reaction time of the relay's electromagnetic circuit and the action time of the relay's contacts (which are both fixed).

The response time of a device is inherent to the device, and in most cases cannot be controlled or eliminated.

The response time specification is useful when assessing the capability of individual devices, such as an actuator for the robot hand, for the purpose of selecting an appropriate actuator for the job.

For some applications the response time of a device or a system may not be important. However in robotic object grasping, manipulation dexterity of the robot hand depends significantly on the response time of the robot hand as a complete system. The response time of a system is simply the sum of the individual response times of all system components.

$$t_{sys} = \Sigma(component\ response\ times) \quad (2)$$

Where,
t_{sys} = system response time.

III. Grasping Performances of Parrallel and Angular Gripper Jaws

Parallel-jaw and angular-jaw grippers have slightly different behavior during object grasping. This section offers a closer look at these grippers to determine what parameters are important in gripper design and why.

A. Parrallel Gripper With One Rigid Jaw

If a parallel-jaw gripper actuator decelerates the gripping jaw at a constant rate (most common) from the point of contact with the object, the gripper jaw will travel a certain distance from the instant at which the gripper stop command was issued by the controller. The travel distance will depend on the gripper reaction time and deceleration time. During reaction time the gripper will continue to travel without deceleration. During the deceleration the deceleration rate will determine the additional distance travelled. Constant deceleration is given by the following equation:

$$-a = dv/dt = constant \quad (3)$$

Where, a = the instantaneous negative acceleration or deceleration which is the rate of velocity change denoted by dv/dt.

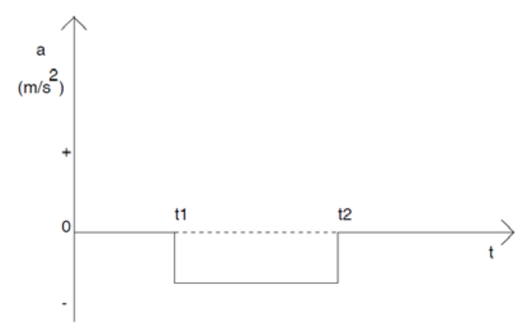

Figure 2. Constant negative acceleration over time

The graph in Figure 2 shows a plot of a gripper jaw constant deceleration over time. Constant deceleration results in a linear velocity decrease as shown in Figure 3 and is given by the following equation:

$$v = ds/dt = linear \quad (4)$$

where v = the instantaneous velocity.

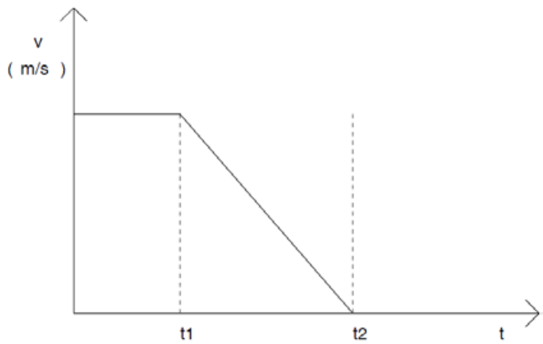

Figure 3. Linear velocity decrease over time

The linear velocity decrease results in a non-linear change in the distance travelled as shown in Figure 3 and is given by the following equation:

$$s = \int v \, dt = \textit{non-linear} \qquad (5)$$

Where, s is the distance travelled up to a point in time, and is found by integrating the velocity up to that point with respect to time.

Integration is useful for finding the area under the curve of non-linear velocity profiles. For a linear velocity profile the distance travelled up to a point in time is simply the geometrical area under the velocity curve up to that point.

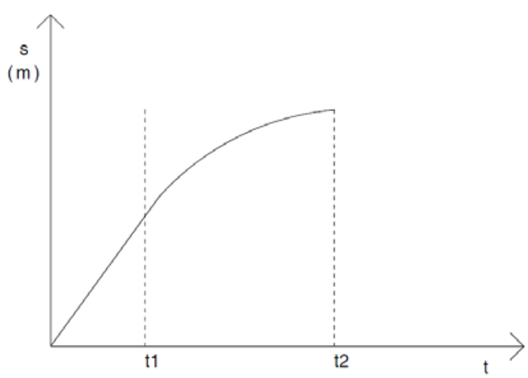

Figure 4. Non-linear distance increase over time

The graph in Figure 4 shows a parallel-jaw gripper response time, including reaction time and deceleration time.

For a parallel-jaw gripper the velocity of the moving jaw is the same at any point along the length of the jaw, so it does not matter which point on the jaw contacts the object first.

The start of the response time should be triggered when the intended grasp force has been reached during grasping. However, the sensor response will not be instantaneous. It will have a response delay, and so will all the other devices in the control chain. These include the following parameters:

- sensor response time;
- sensor signal A/D conversion time;
- digital signal filtering time;
- controller response time;
- actuator response time.

Figure 5. Response time of a parallel-jaw gripper with constant linear deceleration

The graph in Figure 5 demonstrates the moving jaw velocity in real time. The area under the graph in Figure 5 is the total distance travelled by the parallel-jaw gripper from the instant when the intended grasp force was reached and the sensor should have triggered the event, until the instant when the jaw stopped moving.

From these graphs it is evident that the travel distance can be reduced by increasing the deceleration rate of the jaw. The maximum deceleration rate that can be achieved is limited by the response time of the gripper

Note that in the example shown in Figure 5 the “reaction time” area is the same as the “deceleration time” area, although deceleration time takes place over two time units. The obvious way to minimise the stopping distance in this case is to reduce the reaction time to a minimum and increase the deceleration rate to a maximum.

Depending on the actuation technology used, the actuator response time can be significant. Small electric motors under PID (Proportional-Integral-Derivative) control have response times in the millisecond range. When grasping speed is high and gripper jaws are rigid this can be a significant problem, particularly when handling rigid but fragile objects. Due to lack of elastic deformation at the point of contact between a rigid object and a rigid gripper, there isn’t much room for grasping error. Gripper friction, the type of motor-drive combination and the deceleration strategy used will influence significantly the total stopping distance.

B. Angular Gripper With One Rigid Jaw

A similar analysis to that of the parallel-jaw gripper can be conducted for an angular-jaw gripper in terms of the effect of constant deceleration on the gripper performance. Just as for the parallel gripper:

- constant deceleration results in linear velocity decrease;
- linear velocity decrease results in non-linear travel distance with respect to time

The difference between the parallel-jaw gripper and the angular-jaw gripper is that the various points of the moving jaw of the later travel relatively smaller distances closer to the rotation point of the jaw which is at the tip of the jaw. This results in potential over-travel of the jaw tip when grasping an object.

C. *Stopping Distance Performance comparison*

Tests were performed with the parallel-jaw gripper to determine the actual stopping distance from the time the stop command was issued until the jaw stopped. The results of the parallel-jaw gripper stopping distance were used to calculate the stopping distance of an angular-jaw gripper of same dimensions, and under same conditions of actuation and control.

A comparison of the parallel and angular gripper jaw stopping distance is given in Table 1 below for same length gripper jaws. Both, angular and parallel grippers move with a velocity of 100mm/s at the middle of the jaw. Both have a reaction time of 10ms and a deceleration rate of $5000 mm/s^2$. The stopping distance is given independently for reaction time and stopping time. The total stopping distance is the sum of the two distances mentioned earlier in Eqn 1.

The parallel gripper has a total stopping distance of 3mm (1+2). The stopping distance is the same near the bottom of the jaw and near the tip of the jaw.

The angular gripper would have a 1.5mm (0.5+1) stopping distance near the bottom of the jaw, but a large stopping distance of 6mm (2+4) near the tip of the jaw. This is due to the rotation of the jaw around a fixed point at the bottom, rather than parallel translation as in the case of the parallel-jaw gripper.

TABLE I. PARALLEL AND ANGULAR GRIPPER STOPPING PERFORMANCE

	Parallel stop dist [mm]		**Angular stop dist [mm]**	
	React	Decel	React	Decel
Near bottom of jaw	1	2	0.5	1
Near tip of jaw	1	2	2	4

Most humanoid robot hands have articulated fingers that rotate around pivot points, which cause similar behavior as that of the angular gripper. At first glance this does not appear to be an issue. However, when one considers the fact that to achieve reasonable manipulation dexterity the robot hand and fingers have to move fast, it becomes evident that the robot hand control system must respond very fast not only to move commands but even more importantly to stop commands.

IV. RELEVANCE OF MECHANICAL AND SENSING RESOLUTIONS

The mechanical resolution becomes critical when the grasping mechanism moves fast, as is required for high dexterity object manipulation. There are two parameters that are very important in this case:

- Actuator resolution;
- Grasping mechanism's response time.

If the actuator can only control the movement in large increments the robot finger "jumps" in large steps during movement. A typical 1.8 degree stepper motor running in full step mode produces a rough finger movement. A 70mm long finger jumps in about 2mm steps, which is visibly rough. If the grasping mechanism has a slow response time on top of that, the robot hand is of not much use for a practical application. The example summarized in Table 1 shows the stopping performance of two slow gripper designs (the first attempt). If you add a rough actuator such as a 1.8 degrees stepper motor running in full step mode (like we did), you end up with a working but fairly useless robot hand.

The worst case of dynamic sensing resolution takes place when the velocity of the grasping mechanism is the highest. By dynamic sensing resolution we mean the actual sensing resolution during the fastest signal change from min to max. Let's say that a 0 to 5V force sensor's DC signal is sampled using a 10bit A/D converter which can sample at a rate of 100kHz. The smallest change in the signal that the 10 bit A/D converter will detect is 5V / 1023 = 4.9mV, but only if the signal does not change faster than 4.9mV in 10µs. If the sensor value increases from 0 to 5V over a period of 1µs, the signal will be sampled at an effective sampling rate of 10kHz, which means that the actual resolution will be only 49mV. The faster the signal changes, past the sampling rate capability of the A/D converter, the worse the dynamic sensing resolution will be for a given A/D converter resolution and sampling rate.

If the robot finger moving with a speed of 100mm/s, and the force sensor and the robot finger are both rigid, the rate of change of the force sensor output from min to max when it touches a rigid object is very fast. If the signal changes from min to max within 10us, and a resolution of 1/1000 is required, the signal has to be sampled at 10ns intervals, which is equivalent to a sampling rate of 100MHz. This does not allow much room for digital signal filtering which typically requires several samples to create a single filtered signal reading.

If the robot hand travels at 100mm/s and the robot finger has some compliance that produces a change in the sensor output from min to max over a 1mm distance after contact with the object, the rate of signal change is spread over 10ms duration, which results in a significantly slower signal change rate. If we want a resolution of 1/1000 we would have to sample the signal at 10us intervals, which is equivalent to a sampling rate of 100kHz. This allows the control system to sample and process the signal at a comfortable rate. It also allows the control system to control the grasping force reliably, and therefore to produce a controlled grasp action that is capable of handling fragile rigid objects with high confidence.

V. PRINCIPLES FOR PRECISION GRASPING MECHANISM DESIGN

A. Role of Mechanical Resolution

From the mechanical perspective, coarse mechanical resolution limits grasping mechanism's ability to produce a "fine" grasp.

From the object fragility perspective, coarse mechanical resolution limits grasping mechanism's ability to grasp fragile objects safely.

From the slippage control perspective, coarse mechanical resolution limits grasping mechanism's ability to control slippage effectively.

From the sensing perspective, coarse mechanical resolution limits the effective sensor resolution.

B. Role of Force Sensing Resolution

From the control perspective, sensors must provide the grasping controller with the ability to resolve the feedback information with sufficient detail for adequate control. Low sensor resolution may not give sufficient detail of applied forces or distance travelled by the grasping mechanism, which in turn reduces the usefulness of a high mechanical resolution.

From the mechanical perspective, sensors must have sufficient resolution to allow the controller to make full use of the grasping mechanism's mechanical resolution. A low resolution sensor will only allow the control system to resolve the actual force value in coarse steps, which in effect is "hiding" the fine mechanical resolution capability of the grasping mechanism.

C. Role of Mechanical Grasping Resolution

The grasping range limits the maximum and minimum object sizes that can be grasped. We used a cylindrical and a spherical grasping range measure. Our definition of *cylindrical* grasping range is the smallest and largest size cylinder or cylindrical rod that can be grasped and held in a power grasp [3]. Similarly, the *spherical* grasping range is the smallest and largest size sphere that can be grasped and held under control in a power grasp.

Obviously small objects can be grasped between fingertips, but a small object may not necessarily be a light object that can be manipulated using the grasping mechanism's fingertips. The small object could be a handle attached to a heavy object, in which case a power grasp would be needed to grasp the small handle and lift the heavy object.

D. Role of Grasping Force Sensing Range

The sensing range of tactile and force sensors limits the maximum grasp force that can be applied by the grasping mechanism without saturating the sensor output, which in turn causes the sensor to ignore any further increase in the applied grasp force.

Sensitive tactile sensors are useful for detecting small local contact force changes (i.e. small vibration), such as the stick-slip cycles generated during incipient object slippage from the robot hand [4]. However, if the sensor range is exceeded by applying a large grasp force, the sensor will go into saturation. As a result, the benefit of its sensitivity, and therefore its usefulness for incipient slippage detection is lost.

Considering these facts, it is important to note that a single sensor is unlikely to be capable of both, power grasps and fine tactile sensing. Our experimentation and experience shows that in most cases the two force-sensing functions have to be separated such that each is independent of the other, and therefore performed by a different sensor.

VI. CONCLUSION

The paper presents our challenges encountered during grasping mechanism design and commissioning, and believe that these "tips" will be useful to other researchers designing robotic grasping devices, particularly those that do not have a great deal of practical grasping system design and implementation.

It has been showed that grasping mechanism's mechanical and sensing resolution are important for precision grasping because these determine how precisely a grasp can be controlled. Mechanical resolution is significantly different for different gripper designs (e.g. parallel versus angular) even when the same actuator is used. The effective sensor *dynamic* resolution is highly dependent on the rate of grasping force change.

The importance of grasping mechanism's grasping range and sensing range has been briefly explained. The minimum and maximum grasping capacity determines not only the smallest and largest object that can be grasped, but also the graspable range of objects whose size-to-weight ratio is not as expected.

It has been hypothesized that grasping mechanism response time is important for overall grasping dexterity performance. It is also important to be aware of device response times when selecting individual grasping system devices because although individual device response times may be small, when in series with other devices their sum may result in an unacceptable overall response time.

It has been revealed that for some applications the grasping mechanical and sensing resolution will not be important. However, these become critically important for precision grasping and manipulation of rigid but highly fragile objects.

Future work can be done to compile these important grasping mechanism parameters into a simpler and easier to access format. A simulator could be designed to simulate the effects of grasping mechanism's mechanical and sensing resolution, device and system response time, gasping and sensing range, and the effect of sensor signal change rate during grasp force application, which affects the dynamic sensing resolution.

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