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Slip Detection Based Grasp Control of a Robotic Gripper: A Classical Approach

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Abstract— **The grasp control of a robotic gripper poses unique challenges to roboticists owing to the wide horizon of applications associated with robotic end-effectors. The typical control problem requires a gripper to securely grasp an unfamiliar object in an uncertain environment. The complexity of the problem gets compounded with fragile or deformable objects included as candidate grasp-subjects. An intelligent grasp algorithm regulates the grip force using sensor feedback to ensure a secure grasp even in a highly uncertain scenario. This paper attempts to use a slip detection-based feedback scheme that employs a simple and intuitive gain-scheduling-based control law to effectively adapt the grasp force and ensure a secure grasp even under extreme parameter perturbations.**

NOMENCLATURE

D_{ext}	:	External disturbance (N)
F_g	:	Force applied by the gripper jaws (N)
F_{LIFT}	:	External force exerted to lift the gripper and object vertically (N)
T_m	:	Gripper motor torque (Nm)
g	:	Acceleration due to gravity (m/s^2)
i_m	:	Gripper motor current (A)
m	:	Mass of the object (kg)
v_s	:	Slip velocity (m/s)
v_o	:	Vertical velocity of the object (m/s)
v_g	:	Vertical velocity of the gripper (m/s)
W	:	Weight of the object (N)
x_s	:	Distance slipped from the gripper jaws (m)
κ	:	Gripper sensitivity (N/A)
μ_k	:	Coefficient of kinetic friction
μ_s	:	Coefficient of static friction
ξ_G	:	Damping ratio of the gripper actuator
ω_G	:	Bandwidth of the gripper actuator

I. INTRODUCTION: THE GRIPPING PROBLEM!

Robotic gripping solutions have been significantly aiding human activities in various structured and tightly controlled environments such as assembly lines over the past several years [1]. Owing to the high certainty of the environment in which they operate, these robots generally employ a simple open-loop grasping operation. The maximum grasping force for handling each kind of object is pre-calibrated and pre-programmed into the robotic controllers which in turn ensure that, the force exerted by the robots while grasping would never exceed the maximum allowable threshold for each class of object. However, the advent of more and more autonomous robotic applications posed a need for these robotic end-effectors to deal with a variety of objects without knowing their shape, size, texture, or hardness apriori. Thus, control solutions that enable robots to grasp a varied class of objects (hard, soft, or brittle) without potentially deforming or damaging them are in demand.

These unstructured environments represent the next frontier for the robots that grip [1]. Any robot hoping to interact physically with the outside world faces an inherent uncertainty in how objects will react to touch. The mechanics of robot grasping are discussed in [2].

In an unstructured environment, where the robot has no prior knowledge of the object mass or texture, application of excess force can cause the object to break (if it is fragile) or deform (if it is soft) whereas, too little force can cause the object to slip away from the gripper jaws. Hence, it becomes extremely important to determine the optimum force for grasping each object which is just sufficient to prevent it slipping away from within the jaws.

Grasp control algorithms employ a sensor feedback-based mechanism to dynamically adapt the grasp force to prevent slippage. Ding [3] proposed an adaptive back-stepping based control solution using an object-geometry free modelling of the gripper-object interactions. Slip velocity and applied force measurements are employed to estimate the model parameters and adapt the controller. Reference [4] proposed a switched adaptive controller that ensures slip stability for translational and rotational dynamics.

The grasp control problem of robotic end-effectors is a multi-faceted problem that can be tackled only by a confluence of factors including choice of appropriate materials [5], novel bio-inspired gripper mechanisms [6], intelligent closed loop control algorithms and learning based supervisory systems [7].

The focus of this paper is on a slip detection-based feedback control law designed using classical control techniques to ensure secure grasp in a conventional parallel jaw gripper. Compared to the modern control-based techniques discussed in literature, this approach does not require an infinite bandwidth actuation mechanism and is a more viable solution for practical implementation.

The next section describes a typical robotic grasp problem in an uncertain environment involving fragile and deformable objects. The mathematical modelling and control architecture adopted are described in section III and IV respectively. The effectiveness of the proposed solution in addressing the wide

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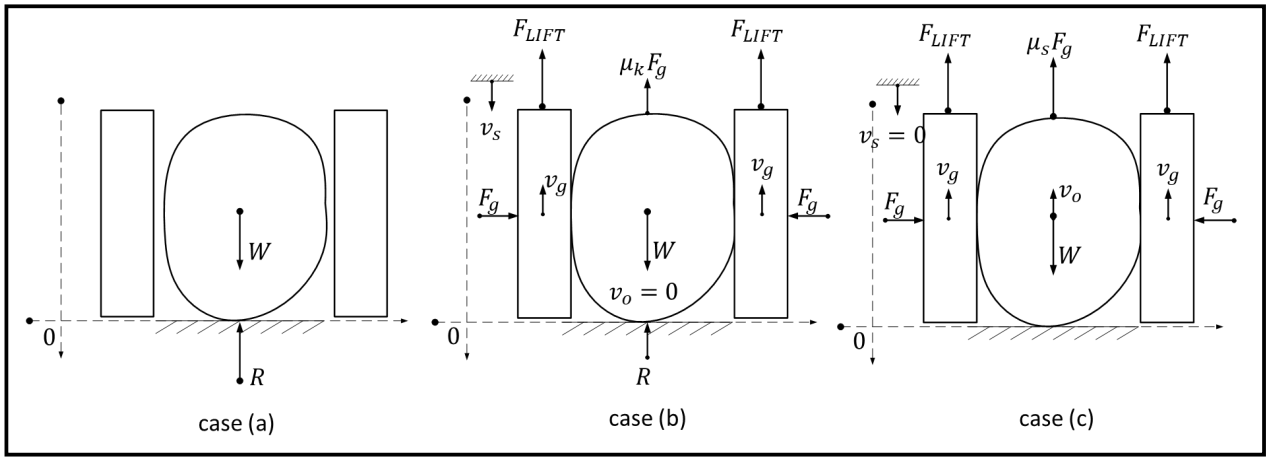


Figure 1. Free-body diagrams showing different stages of the object-gripper interaction

range of parameter uncertainties anticipated in real world grasping is demonstrated through the simulation results in section V. Section VI concludes the discussion.

II. Problem Statement

Consider the grasp problem of an irregular shaped, deformable object by a parallel jaw gripper. The different stages of the object-gripper interaction are detailed using the free body diagrams shown in Fig 1. Initially, an object resting freely on a support structure is considered (case (a)). In this condition, the weight of the object (W) is balanced completely by the normal reaction (R) from the support structure. The gripper force (F_g) is a measured reaction force and does not develop until the gripper encounters the object.

Once the gripper meets the object (case (b)), a frictional force develops that tends to oppose any relative movement between the gripper and the object. The object is in 'secure grasp' when the relative movement between the gripper jaws and object is completely arrested. The relative velocity of the object (v_o) measured with respect to the velocity of the gripper jaws (v_g) is defined as the slip velocity (v_s).

$$v_s = v_o - v_g \tag{1}$$

When the object is in secure grasp, the coefficient of static friction (μ_s) opposes ensuing of slip. Similarly, under slipping condition, the coefficient of kinetic friction (μ_k) opposes slip. The frictional force ($F_{friction}$) is proportional to the grasp force (F_g) exerted by the gripper.

At a given instant of time, when the magnitude of the frictional force generated by the gripper is less than the weight of the object, if the object-gripper assembly is lifted by a force F_{LIFT}, a slip develops between the gripper and the object and the gripper slides upward, leaving the object still on the support structure. However, if while lifting the gripper, the gripper force was sufficient to balance the weight of the object and the inertial forces due to the lifting acceleration, the gripper would lift the object up without any slippage resulting in secure grasp.

It can be noted that by ensuring a sufficiently high grasp force, the frictional forces can balance the weight of the object and ensure secure grasp for a rigid object. However, if the candidate object to be grasped include fragile or deformable items, an excessive grasp force may deform or damage the item. Such scenario demands regulation of gripper force to a value just enough to balance the weight of the object ensuring secure grasp.

The grasp control problem hence boils down to computing and regulating the gripper force to balance the weight of the object. The uncertainties in mass (m) of the object, the coefficient of friction between the object and gripper and the lifting velocity profiles necessitates a feedback based closed loop control of grasp force to ensure secure grasp under wide-range of parameter uncertainties. This paper proposes a slip detection-based gain-scheduling scheme, that uses the measured slip velocities to adjust grasp force in closed loop.

III. Mathematical Modelling

A. Stages of Grasp: Object-Gripper Interactions

The mathematical model for the different phases of the object-gripper interaction is written based on the free body diagrams shown in Fig 1. The various phases identified are:

a) When the object is completely supported ($R = mg$) and no slippage ($v = 0$):

$$\dot{v}_o = \frac{1}{m}(W - R) = 0 \tag{2}$$

This condition arises when the gripper has not yet contacted the object.

b) When the object is supported ($R > 0$) and the gripper is lifted by an external force F_{LIFT}.

If there exists a slippage between the gripper and object ($v_s > 0$):

$$\dot{v}_o = \frac{1}{m}\left(-\mu_k F_g + W - R\right) \tag{3}$$

This condition arises when the gripper and object are

in contact, and the gripper is lifted by the arm. However, as the grasp force was insufficient, the object starts slipping out of the gripper jaws.

c) When the object is unsupported ($R = 0$) and no slippage ($v_s = 0$):

Gradually, when the grasp force is sufficient to balance the weight and prevent slip, normal reaction disappears. As there is no slippage between the object and gripper, the coefficient of static friction comes into effect.

$$\dot{v}_o = \dot{v}_g \tag{4}$$

This is a case of secure grasp. The object is secure in the jaws of the gripper and there is no further change in object velocity relative to the gripper jaw. The object and gripper now move together.

d) When the object is unsupported ($R = 0$) and there exists a slippage between the gripper and object ($v_s > 0$):

$$\dot{v}_o = \frac{1}{m}\left(-\mu_k F_g + W + D_{ext}\right) \tag{5}$$

This case occurs when a slip develops after the object was grasped and the gripper started moving up. This is usually caused by sudden jerks or disturbances from the robotic arm or external disturbances. The term D_{ext} denotes the external disturbance force (N) due to gripper acceleration.

In each phase, the object dynamics described in equations (2), (3), (4), or (5) are integrated to compute the object's vertical velocity. For this study, it is assumed that the gripper is lifted at a constant upward velocity (v_g) without any sudden acceleration/ jerk). A velocity-controlled mode of operation of the actuator responsible for the upward movement of the gripper assembly could ensure this condition in practice.

B. The Perturbation Model

From the discussions in the previous section, it can be noted that, for secure grasp, the gripper must apply a certain minimum grasp force to balance the weight of the object and prevent slippage. In the absence of external disturbances, the minimum grasp force required to balance the object weight can be readily computed from (5) as:

$$F_{g_0} = \frac{W}{\mu_k} \tag{6}$$

However, this force ensures static equilibrium only when the parameters, object mass (m) and the coefficient of friction (μ_k) are precisely known. Further, any dynamic change in the gripper velocity (v_g) can also upset the balance and cause the object to slip away from the gripper jaws. The dynamic equations describing the object slippage from the gripper jaws can be derived using (1) and (5) as,

$$\frac{d}{dt}(v_s) = \frac{1}{m}\left(-\mu_k F_g + W\right) - \dot{v}_g \tag{7}$$

Let the nominal values of the parameters mass and coefficient of friction be denoted by m_0 and μ_{k_0} respectively.

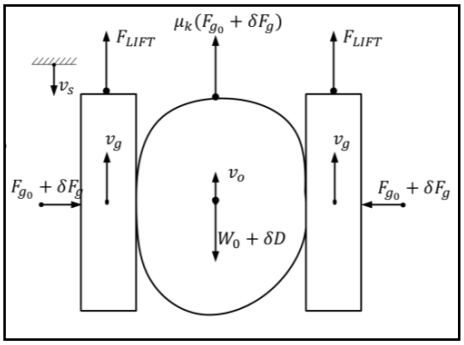


Figure 2. Free body diagram for the perturbation model

The dynamic equation including the parameter uncertainties (δm and $\delta\mu_k$) can then be re-written as:

$$\dot{v}_s = \frac{-\left(\mu_{k_0} + \delta\mu_k\right)(F_{g_0} + \delta F_g)}{(m_0 + \delta m)} + g - \dot{v}_g \tag{8}$$

Dynamic equilibrium can be ensured only if $\dot{v} = 0$. i.e.,

$$\left(\mu_{k_0} + \delta\mu_k\right)(F_{g_0} + \delta F_g) = (m_0 + \delta m)(g - \dot{v}_g) \tag{9}$$

On re-arranging we get,

$$\left(\mu_{k_0} + \delta\mu_k\right)\delta F_g = \delta m g - (m_0 + \delta m)\dot{v}_g - \delta\mu_k F_{g_0} \tag{10}$$

A disturbance input δD is defined as:

$$\delta D = \left((m_0 + \delta m)\dot{v}_g + \delta\mu_k F_{g_0} - \delta m g\right) \tag{11}$$

The term δD represents the incremental effects of the parameter uncertainties and external disturbances on the object-gripper interaction when the equilibrium grasp force is applied.

Substituting (10) and (11) in (8) we get,

$$(m_0 + \delta m)\dot{v}_s = -\left(\mu_{k_0} + \delta\mu_k\right)\delta F_g + \delta D \tag{12}$$

The perturbation model for the object-gripper interaction is then obtained as:

$$m\,\dot{v}_s = -\mu_k\,\delta F_g + \delta D \tag{13}$$

where, δF_g is the incremental grasp force adjustments required to prevent the object slippage (Fig 2).

Once the secure grasp is established, and the object is being lifted by a gripper, then the real-time grasp force adjustments necessary to ensure dynamic equilibrium is determined using this perturbation model. A slip feedback based closed loop control scheme is devised to ensure dynamic stability even under wide range of parameter uncertainties.

B. Actuation and Sensing Mechanism

The block diagram of the grasp control loop including the sensing and actuation elements is shown in Fig. 3. Closed loop regulation of grasp force requires an actuation system of reasonably high bandwidth to precisely regulate the grasp force based on the instantaneous slip feedback.

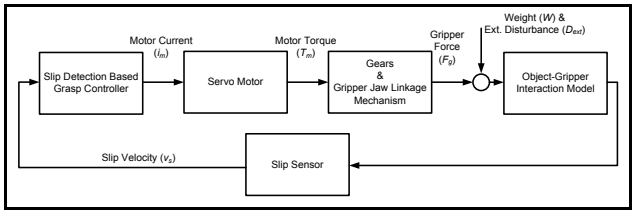


Figure 3. Block diagram of the grasp control loop

A servo motor-based actuation mechanism capable of torque control mode of operation is employed as the actuation mechanism. In the linear range of operation, the load torque output of the servo motor (T_m) is directly proportional to the motor current (i_m).

$$T_m \propto i_m \tag{14}$$

As discussed in section II, the gripper force is a reaction force and develops only when the gripper and object are in contact. Once in contact, the gripper jaws exert a force against the object trying to grasp it. The force exerted by the gripper is proportional to the incremental jaw displacement after establishing contact with the object.

However, to achieve and sustain a certain gripper jaw displacement under loaded conditions, the servo motor of the gripper applies a constant torque and draws a steady current. Therefore, the steady value of the applied gripper force F_g is proportional to the current drawn by the servo motor.

$$F_g = \kappa\, i_m \tag{15}$$

where κ is the sensitivity of the gripper to the input current.

In addition, the delay in gripper response due to the dynamic characteristics of the motor and the gripper linkage mechanisms are captured by using a second order transfer function.

$$\frac{F_g(s)}{i_m(s)} = \frac{\kappa\, \omega_G^2}{s^2 + 2\xi_G \omega_G + \omega_G^2} \tag{16}$$

As evident from Fig. 3, the closed loop grasp control algorithm proposed in this paper works based on slip measurement. Several slip detection techniques have been discussed in literature like tactile sensor arrays [8], optical sensing [3] etc. For this study, it is assumed that the sensor hardware and sensor data processing algorithm operate at a considerably higher rate compared to the control loop. Hence the sensor dynamics are ignored and the slip measurement (v_s) is assumed to be directly available for the control computations.

IV. The Control Architecture

The control challenge in grasping fragile objects is to regulate grasp force precisely to balance the weight of the object and the external disturbances without putting undue force on the fragile structure. In an uncertain environment, the grasp force regulation problem becomes complicated as time available to react and correct for the parameter uncertainties and external disturbances is very low (i.e. before the object slips out of the gripper jaws). As the maximum tolerable force of the object to be grasped is not known beforehand, the control solutions get further crippled by the constraint that the slip must be arrested with near-zero overshoot in grasp force.

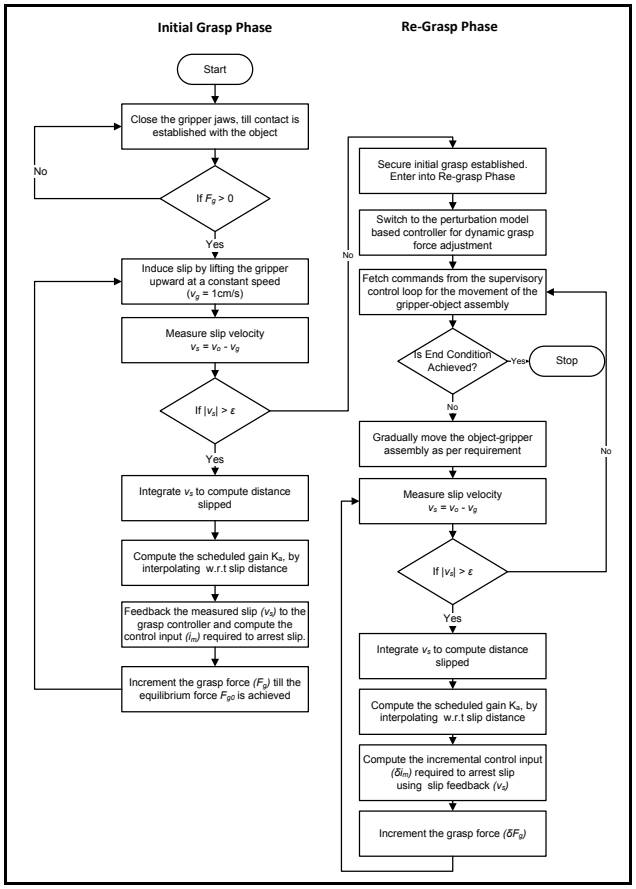


Figure 4. Flow chart of the two-step grasp algorithm

Preliminary investigations in the design space revealed that, grasping a fragile object mid-air, would require a near infinite bandwidth control and actuation systems and are infeasible for practical solutions. In this paper, the control problem is simplified by assuming that initially, the object to be grasped is at rest on a support structure. Without loss of generality, it can be seen that this is the case in most practical grasp applications. A two-step grasp logic is being proposed for arresting slip. In the first step, while the object remains supported, the grasp force is gradually regulated in closed loop till it reaches the equilibrium value necessary to balance the weight of the object. This phase is called the initial grasp phase and allows for a regulated slip (only the gripper moves up at a constant uniform velocity and the object remains at rest) in the beginning. The grasp force is gradually increased to arrest slip without any undue overshoots which could damage the grasped object. This scheme eliminates the need for an infinite bandwidth actuator and makes the control solution feasible for practical implementation.

Once the secure grasp is established and the slip velocity is brought to a very low value, the gripper lifts the object from the support structure. In this phase, all the parameter uncertainties and external disturbances might lead to further slippage of the object from the gripper jaws. The perturbation model of the object-gripper described in (13) is employed and a slip feedback based classical control law is designed to sense and arrest any such incipient slip. This is called the re-grasping phase and regulates grasp force incrementally (δF_g) to bring the slip velocity back to zero and regain secure grasp. The detailed flow chart of the proposed two-step grasp algorithm is shown in Fig.4.

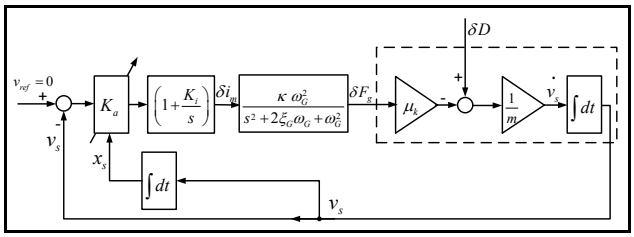


Figure 5. Control loop structure for the re-grasping phase

A quick inspection of the perturbation model from (13) reveals that in order to ensure dynamic equilibrium of the perturbation model both the slip velocity v_s and its derivative $\dot{v}_s$ are to be brought to zero. A proportional-integral control structure is essential to ensure this objective. The integrator also actively rejects the disturbances due to external disturbances. The control loop structure for re-grasping phase is shown in Fig. 5.

The uncertainties in plant parameters μ_k and m could lead to an insufficient adjustment of grasp force and slippage. To manage this scenario, the feedback controller gains are scheduled as a function of slip distance (x_s) to ensure that, the gain of grasp force is increased significantly if the object slips beyond a certain minimum threshold.

V. RESULTS AND DISCUSSION

As discussed in section IV, the purpose of the initial grasp phase is to increase the grasp force gradually to the value necessary to balance the weight of the object. One of the solutions to this problem is to have a feed-forward grasp force term in the controller loop which can be tuned to the nominal value. However, to avoid any undue overshoots in grasp force that may result from parameter uncertainties, the option described in section IV was finalized. The gripper is gradually lifted with a constant velocity of 1cm/s. The resulting slip is used to adjust grasp force in closed loop.

Similarly, in the re-grasping phase, the small signal perturbation model from (13) is used for the feedback control law design. For the simulation studies, the second order actuation dynamics from (16) is included and a third order state-space model of the plant dynamics is computed with states $X = [v_s,\ F_g, \dot{F}_g]^T$. The state space matrices are:

$$A = \begin{bmatrix} 0 & -\frac{\mu_k}{m} & 0 \\ 0 & 0 & 1 \\ 0 & -\omega_G^2 & -2\xi_G\omega_G \end{bmatrix} \quad B = \begin{bmatrix} 0 & \frac{\delta D}{m} \\ 0 & 0 \\ \kappa\,\omega_G^2 & 0 \end{bmatrix} \qquad (17)$$

$$C = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \end{bmatrix},\ D = \begin{bmatrix} 0 & 0 \\ 0 & 0 \end{bmatrix}$$

The first input of the state-space model corresponds to the current of the servo motor (δi_m), which is the control input. The second input is the disturbance term δD due to parameter uncertainties and external disturbances defined in (11).

TABLE I. NOMINAL VALUE OF PLANT PARAMETERS

Parameter	Symbol	Value
mass of the object	m	0.1 kg
coefficient of static friction	μ_s	0.5
coefficient of kinetic friction	μ_k	0.375
sensitivity of the gripper	κ	12.212 N/mA
bandwidth of actuator	ω_G	10 Hz
damping ratio of actuator	ξ_G	0.7
forward path gain	K_a	-0.1743
integrator gain	K_i	4
initial gripper velocity	v_g	0.001 m/s

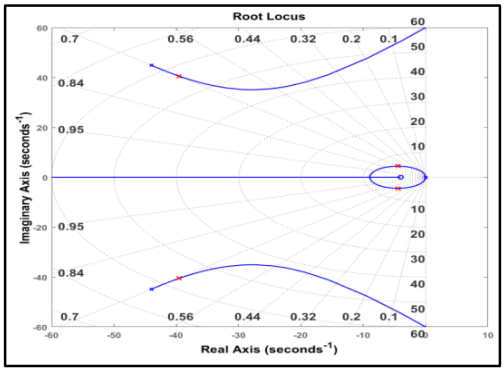


Figure 6. Root locus of the open loop plant with controller

The nominal value of the parameters considered for the controller design are listed in Table 1. The integral gain K_i is designed to arrest the slip adequately fast while preventing overshoots in grasp force even under parameter perturbations. The forward path gain K_a is designed using root locus plot (Fig. 6) to ensure a closed loop bandwidth in the range of 4-5 rad/s, closed loop damping of 0.7 and adequate stability (phase margin > 50 deg and gain margin > 20 dB) margins.

The closed loop system behavior under an initial slip capture for a nominal scenario and with object mass perturbed by 100% is shown in Fig. 7. Because of the ratio (μ_k/m) in the plant model (17), increasing mass by 100% is equivalent to reducing μ_k by 50%. Even under extreme perturbations, the control algorithm ensures secure grasp without any overshoot thus ensuring protection of fragile objects. The results also demonstrates that, the object remains within the jaws of the parallel gripper (distance slipped is less than the jaw length of

10cm) under all perturbations. Scheduling the forward path gains w.r.t slip distance led to significant improvements in the initial slip capture (distance slipped reduced to 4cm from 5cm).

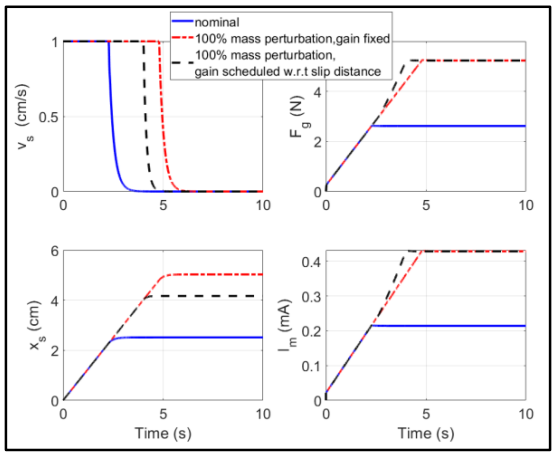


Figure 7. Initial slip capture: nominal and off-nominal plant

Further, the controller performance under re-grasp phase is evaluated by linearly increasing the object mass after the initial slip capture. This simulation is equivalent to an experimental demonstration of grasp quality by gradual addition of some liquid into an empty cup securely grasped by a parallel jaw gripper. It can be seen from the simulation results (Fig. 9) that, when the mass is added gradually, even up to double its nominal value, the grasp controller automatically adjusted the grasp force to arrest slip quite effectively without leading to any overshoots in grasp force. The additional distance slipped due to dynamic change in payload mass is incremental and the object still remains secure in the gripper jaws. The forward path gain is adapted continuously based on the increasing slip distance (Fig. 8) to increase the grasp force before the object slips out of the gripper fingers.

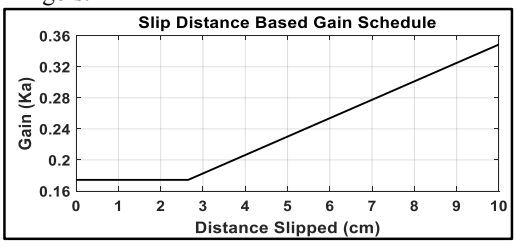


Figure 8. Slip distance-based gain schedule

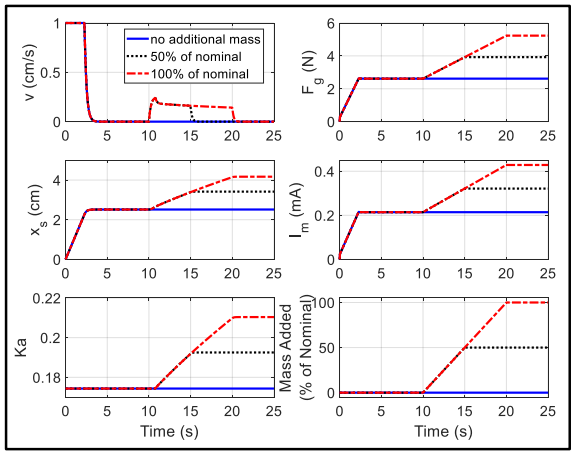


Figure 9. Regrasp phase: dynamic adjustment of grasp force

VI. CONCLUSIONS AND FUTURE SCOPE

This paper proposes a novel slip detection-based feedback control system designed using classical control technique for grasp control of a robotic gripper intended to operate in highly unfamiliar/uncertain environment. The simulation results demonstrate the ability of the proposed algorithm to cater to wide range of parameter uncertainties. The simulations also showcase the ability of the controller to dynamically adjust and gracefully recover the performance even when the plant parameters are disturbed on the go.

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