

Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering

<http://pii.sagepub.com/>

Dynamic capture of free-moving objects

A Nagendran, W Crowther and R C Richardson

Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering published online 13 August 2011

DOI: 10.1177/0959651811407659

The online version of this article can be found at:

<http://pii.sagepub.com/content/early/2011/08/13/0959651811407659>

Published by:



<http://www.sagepublications.com>

On behalf of:



[Institution of Mechanical Engineers](#)

Additional services and information for *Proceedings of the Institution of Mechanical Engineers, Part I: Journal of Systems and Control Engineering* can be found at:

Email Alerts: <http://pii.sagepub.com/cgi/alerts>

Subscriptions: <http://pii.sagepub.com/subscriptions>

Reprints: <http://www.sagepub.com/journalsReprints.nav>

Permissions: <http://www.sagepub.com/journalsPermissions.nav>

>> [Proof](#) - Aug 13, 2011

[What is This?](#)

Dynamic capture of free-moving objects

A Nagendran^{1*}, W Crowther², and R C Richardson³

¹Institute for Simulation and Training, University of Central Florida, Orlando, Florida, USA

²School of Mechanical, Aerospace and Civil Engineering, University of Manchester, Manchester, UK

³School of Mechanical Engineering, University of Leeds, Leeds, UK

The manuscript was received on 25 October 2010 and was accepted after revision for publication on 30 March 2011.

DOI: 10.1177/0959651811407659

Abstract: A new stiffness control method is proposed for robotic systems to capture free-moving objects with minimum jerk. A bell-shaped stiffness curve is shown to minimize the jerk that occurs during capture tasks. The results verify that the method can be used to successfully decelerate objects over a predefined distance, while keeping the jerk experienced during the capture within limits. Shortcomings with the method are identified from the results, and an adaptive control scheme is proposed. An adaptive controller is designed to actively interact with the object to estimate the kinetic energy during the capture and scale the amount of force being applied accordingly. Simulation results confirm that the adaptive control scheme overcomes the shortcomings in previous methods.

Keywords: dynamics, robot arm, impedance control, self-tuning control, identification

1 INTRODUCTION

To catch an object is to bring it from free flight to rest. The ability to consistently capture moving objects can be particularly useful in areas such as the docking of spacecraft and in sports. Catching a ball using a baseball glove [1], dynamic pick and place of objects using a robot [2], and juggling and catching balls [3, 4] have been studied previously.

Capture involves three phases:

- movement of the capture system to intercept the free-moving object;
- joining with (or holding) the object so that both the capture system and object are interlinked;
- applying forces to the object to bring it to rest at specified coordinates.

The majority of the literature in the area describes trajectory planning and interception of the object before the catch, i.e. phase 1. In general, these methods involve: detecting the object; determining

when it is in flight; tracking and predicting the object's trajectory; and planning and executing a movement to intercept the object [5–11].

On completion of the interception phase, it is expected that there is a minimal mismatch in the velocities of the object and capture system so as to minimize impact. Then, a movement (closure) of the gripper of the capture mechanism at the instant of contact causes the object and the capture system to link (Phase 2). Once the capture system and object are interlinked (phase 3) suitable forces must be applied to decelerate the object so that it does not become damaged and it comes to rest at the required location.

When a force is applied to a mass, it is subject to a change in acceleration. The rate of change of acceleration is called jerk. High levels of jerk have the potential to cause damage to both the manipulator and the object being captured. This effect is more evident in delicate or flexible structures [12, 13]. The significance of jerk is that it adversely affects the efficiency of the control algorithms resulting in an increase in joint position errors [14]. Jerk also affects the overall stability of the system and causes vibrations of the manipulator, and hence must be minimized [15]. Limitation of jerk results in

*Corresponding author: Institute for Simulation and Training, University of Central Florida, Orlando, FL 32826, USA.
email: arjun@cs.ucf.edu

improved path tracking, reduced wear on the robot, and smoothed actuator loads [16].

In this paper a dynamic capture approach is proposed to decelerate objects while minimizing the jerk applied to the object, and bring it to rest at specified position in the presence of uncertainty in object mass and velocity. Section 2 introduces the theoretical background and section 3 investigates how to deal with uncertainty in capture-object characteristics. Section 4 experimentally tests a capture with a system based around electric motors, and investigates a self-tuning approach in simulation. Finally section 5 draws conclusions from the work.

2 CAPTURE WITH MINIMUM JERK

Here it is assumed that the capture system will consist of a two-joint serial-link revolute manipulator with an end effector to grasp the flying object. Once the end effector has been positioned to intercept the object (using position control), it is required to grasp the object, and then decelerate it to rest over a predefined workspace. A commonly proposed method of object deceleration is to control the position of the capture systems once the object is held. Computed torque control can be used for open-loop trajectory control of the end effector, following the impact phase [5, 6]. It is particularly useful to couple it with a proportional-derivative (PD) controller to perform trajectory tracking of the end effector during the post-capture phase (once impact between the mass and tip is complete) of dynamic mass capture [7]. However, pure position control prevents direct control of the deceleration force. Conversely, force-only controllers are not capable of bringing an object to rest at defined coordinates.

Interaction controllers regulate the relationship between force and position. There are two commonly used interaction controllers: hybrid (force/position) [17] and impedance control [18]. Hybrid force and position controllers separate position and force into controller planes, essentially decoupling them. The challenge with hybrid force and position control is to identify where the force and position planes should be implemented; in the capture situation these are particularly poorly defined. With impedance control, a dynamic relationship between force and position is established such that a change in position results in the application of a force defined by the impedance relationship. The target impedance is specified by the user, and the corresponding force can be computed using

the second-order continuous equation describing the impedance control as

$$F(t) = M\ddot{X}(t) + C\dot{X}(t) + K[X(t) - X_0(t)] \quad (1)$$

where X_0 is the equilibrium position of the end effector. In terms of the actual implementation, the robot can be thought of as an inertial mechanism driven by actuators with controllable torques so that the dynamic equation now becomes

$$\tau = \mathbf{I}(\theta)\ddot{\theta} + \mathbf{c}(\dot{\theta}, \theta)\dot{\theta} + \mathbf{g}(\theta) \quad (2)$$

where τ is the vector of joint torques, θ is the n -dimensional joint-space position vector, $\mathbf{I}(\theta)$ is an $n \times n$ symmetric inertia matrix, $\mathbf{c}(\dot{\theta}, \theta)$ is the $n \times n$ tensor or velocity coupling matrix, where n is the number of joints, and $\mathbf{g}$ is the $n \times 1$ gravity-dependent vector. In equation (2), the first term on the right-hand side represents the inertial forces, the second term represents the Coriolis and centripetal forces, and the third term is the force due to gravity.

To illustrate the performance of a spring and damper for capture it is useful to consider controllers acting as a pure spring or a spring and damper. As the desired deceleration distance is known, values of K and C can be chosen by consideration of kinetic energy to decelerate the mass. Non-dimensional analysis [19] revealed a high jerk in both cases, when the impedance control was used to capture an object of 5 kg mass moving at a velocity of 5 m/s (Fig. 1). This is attributed to the fact that a spring continues to apply a force proportional to displacement even after the body is brought to rest, resulting in the jerk spike at the end of capture. With a damper, the system applies a force proportional to the velocity initially, resulting in a high jerk at the beginning of the capture.

In order to keep the jerk to a minimum, a new method of control is proposed, where the relationship between force and position is in the form of a bell curve. The bell curve overcomes the drawbacks of both the spring and spring-damper systems by applying a smooth changing force at the beginning as well as the end of the capture. Although this relationship is termed impedance, impedance control is usually associated with mass-spring and damper response [18]. In this paper, a function that models a non-linear impedance relationship is described, which requires the controller to handle both the constrained and unconstrained stages during manipulator motion [20]. Therefore, this controller is described as stiffness control to avoid confusion. The desired bell-shaped curve is implemented using the following well understood cosine equation

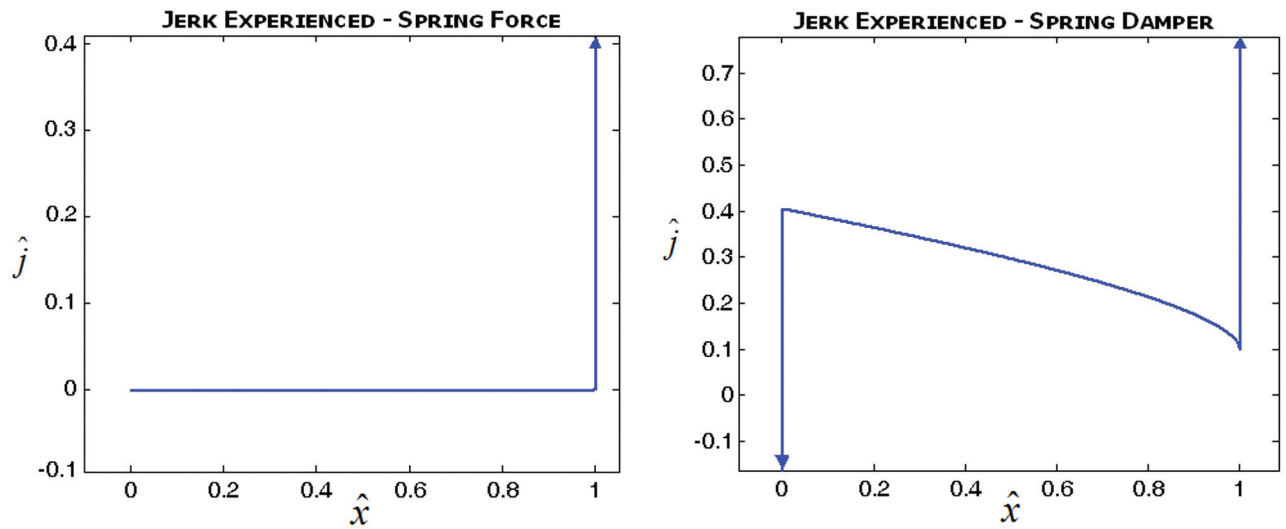


Fig. 1 Analysis of jerk when target impedance is (a) a spring ($\zeta=0$) and (b) a critically damped spring-damper system ($\zeta=c/2\sqrt{km}=1$)

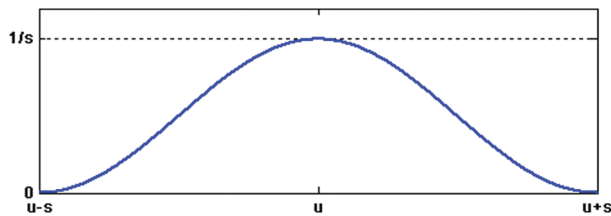


Fig. 2 Raised cosine distribution: bell shaped

$$f(x; u, s) = \frac{1}{2s} \left[1 + \cos\left(\frac{x-u}{s} \pi\right) \right] \quad (3)$$

that is supported in the interval $u-s$ to $u+s$. The maximum value of the resulting curve is $1/s$, which occurs at $x=u$ (Fig. 2). In terms of the actual stiffness relationship, the x -axis on the figure relates to a change in position of the robot end effector, while the y -axis indicates the force being applied at the end effector in response to that change.

From equation (3), the distance over which the object must decelerate is between $(u-s)$ and $(u+s)$. Hence, u and s are chosen as half the maximum distance. Because the maximum amplitude is dependent on s , a scaling factor is required to implement maximum deceleration for a given distance. Hence, equation (3) is modified to include a scaling factor A , chosen such that A/s is the maximum force tolerable. If the maximum deceleration is known, the maximum force tolerable by the object can be computed using D'Alembert's principle

$$F(t) - M\ddot{X}(t) = 0 \quad (4)$$

where M is the mass of the object, $F(t)$ is the force, and $\ddot{X}(t)$ is the acceleration at instant t . Equation (3) can be written in terms of force and position as

$$F(t) = \frac{A}{2s} \left[1 + \cos\left(\frac{X(t) - u}{s} \pi\right) \right] \quad (5)$$

Equation (5) results in a force being output depending on the position of the object and ensures that the deceleration of the object is kept within the tolerable limit. It is important to note that the area under this bell curve determines the total work done, and in order to decelerate the body to a complete halt, this must be equal to the total kinetic energy of the object.

The area under this bell curve is 50 per cent of the total area under the rectangle with sides equal to the maximum force and maximum distance over which the body decelerates. This bell-shaped profile is suitable for dynamic mass capture, since the resultant jerk profile is a smooth curve with no spikes at the beginning or end of the capture process. This was verified by decelerating a 5 kg mass moving at 5 m/s over the same predefined distance as when a spring or spring-damper were used. The results [19] show that the amount of jerk is greatly reduced if a bell-shaped curve of force against position is used to capture the object (Fig. 3).

An added advantage with this method of control is that the force increases and decreases gradually. An actuator's inherent dynamics prevent it from applying quickly changing forces, and as a result,

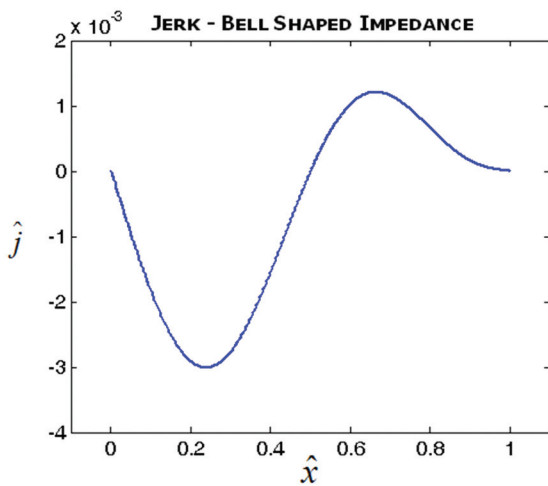


Fig. 3 Jerk when bell-shaped stiffness control is used

the smooth bell-shaped profile makes it simpler and more accurate to implement.

3 DEALING WITH UNCERTAINTY IN THE PROPERTIES OF THE CAPTURE OBJECT

It is likely that the estimation of the mass or velocity of the capture object will be inaccurate, resulting in the proposed bell curve decelerating the object either too quickly or too slowly. It is possible to adjust the bell curve during capture to ensure that the object is always decelerated over the correct distance and comes to rest at the desired coordinates. The performance specifications of the controller can be summarized as:

- given the workspace of the manipulator, decelerate a mass to rest within 50 per cent of the available linear displacement;
- implement the desired stiffness to within 10 per cent accuracy;
- minimize jerk during the capture process.

3.1 Parameter estimation to determine mass

Once the object is held and being decelerated, a real-time estimate of the mass can be found through analysis of the forces applied and resultant deceleration. The continuous-time dependent equation (4) can be converted to the frequency domain using the Laplace transform, which is a linear operator, operating on a function with a real argument ($t, t \geq 0$), and transforming it into a function with a complex argument(s), that is

$$\frac{X(s)}{M(s)} = \frac{1}{Ms^2} \quad (6)$$

Equation (6) is the transfer function for the system being considered. The continuous-time transfer function – represented in the s -domain – given by equation (6) is converted to discrete time using the bilinear transform. The resulting equation is not strictly causal, and therefore a delay with one sample between output and input has been included to make the equation causal (equation (7)); for a high sample rate this has negligible effect on the system impedance

$$F[z^{-1}] \frac{T^2}{2} [(z^{-1} + z^{-2})] = X[z^{-1}] (z^{-1} - 2z^{-2} + z^{-3}) M \quad (7)$$

The difference equation for the system given by equation (7) fits the following general form

$$y_t = q_t b_0 \quad (8)$$

where y_t and q_t are the output and input samples at instant t , as computed from equation (7). Comparing equations (7) and (8) it follows that

$$y = F[z^{-1}] \frac{T^2}{2} [(z^{-1} + z^{-2})] \\ q = X[z^{-1}] (z^{-1} - 2z^{-2} + z^{-3}), \quad b_0 = M$$

with T representing the sampling time. However, noise and measurement error can result in identification errors. It is possible to obtain an unbiased estimate of parameters only when the equation error has a white noise character. A common approach is to use overloaded vectors (many input and output data points) to identify a small number of coefficients. The major component of electrical sensor noise is normally white noise and therefore this approach is appropriate. The least squares technique [21] is of the form

$$y = \psi \theta \quad (9)$$

where

$$\theta = [M], \quad \psi = [u_i], \quad y = [y_i] \quad (10)$$

In equation (9), y is the output vector, ψ is the regressor matrix, and θ is the parameter vector; $[u_i]$ and $[y_i]$ in equation (10) indicate the input and output samples over time, while M is the unknown parameter being estimated, i.e. the mass of the object. The parameter vector estimate ($\hat{\theta}$) based on samples up to sample instant t can be obtained using

$$\hat{\theta}_t = (\psi_t^T \psi_t)^{-1} \psi_t^T y_t \quad (11)$$

This estimate $\hat{\theta}$ can be used in equation (9) to predict the current plant values based on the previous input and output values, that is

$$\hat{y} = \psi^T \hat{\theta} \quad (12)$$

where $\hat{y}$ denotes the predicted output value. In a real-time system, large amounts of input/output data is not known in advance. Therefore, the recursive least squares algorithm [21] can be used to self-tune the estimate in real-time. Essentially, the recursive least squares algorithm uses current input/output data to improve identification estimates but also remembers previous estimates. This leads to a convergence to a particular identified set of parameters, with data obtained after a period of time having negligible influence on the estimate.

3.2 Steps of the recursive least squares algorithm [21]

1. Determine the plant input and plant output samples y_t and q_t at sampling instant t where $y = F[z^{-1}] \frac{T^2}{2} [(z^{-1} + z^{-2})]$ and $q = X[z^{-1}](z^{-1} - 2z^{-2} + z^{-3})$.
2. Form the regressor vector $\omega_t = [y_t]$.
3. Calculate k_t using $k_t = P_{t-1}[y_t] / \{1 + [y_t]^T P_{t-1}[y_t]\}$.
4. Update the parameter vector estimate as $\hat{\theta}_t = \hat{\theta}_{t-1} + k_t \{q_t - [y_t]^T \hat{\theta}_{t-1}\}$.
5. Update P_t for the next sample instant $P_t = P_{t-1} - k_t [y_t]^T P_{t-1}$.

The regressor vector in the steps above can be constructed only after several samples have been collected. The rate of change of the parameter vector estimate between sample instants is controlled by P_t . If the initial estimate of mass is very inaccurate, a high value of P_t causes the estimates to change very quickly towards more accurate values, but may cause instability. Conversely, a low value of P_t may cause the system to lose sensitivity, in which case the parameter estimate vector tends to converge to incorrect parameters. This can result in a failed capture but does not directly affect the stability of the control process itself.

To justify the chosen value of P_t , several simulations were performed with the criteria that the initial mass estimate had an error of 25 percent (both overestimation and underestimation) with respect to the actual mass (Fig. 4, Fig. 5). It was found that the chosen value of P_t (1×10^{11}) was suitable for parameter estimation, without causing any overestimation or underestimation of the actual mass, when

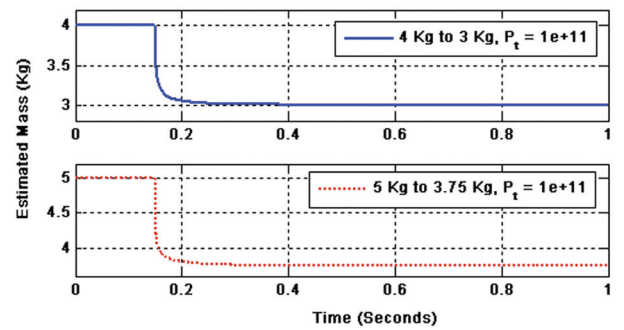


Fig. 4 Chosen value of P_t appropriate for overestimation of mass within 25 percent error (a) initial estimate of 4 kg corrected to 3 kg and (b) initial estimate of 5 kg corrected to 3.75 kg

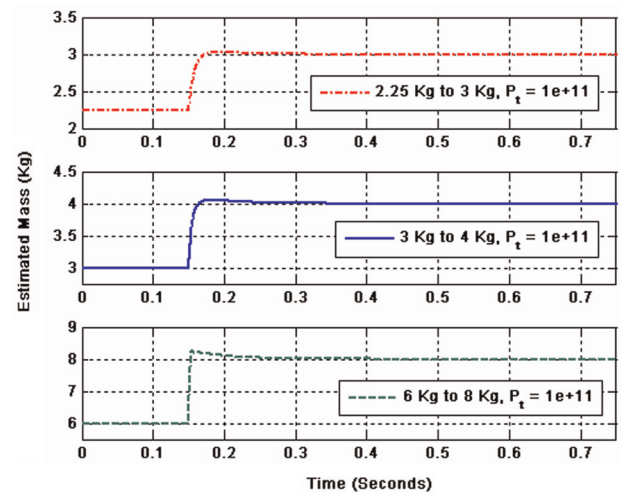


Fig. 5 (a) Initial estimate of 2.25 kg corrected to 3 kg; (b) initial estimate of 3 kg corrected to 4 kg; and (c) initial estimate of 6 kg corrected to 8 kg

the initial estimate was within 25 percent error of the actual mass.

3.3 Online velocity estimation

Once the mass of the object at the time of capture has been determined, the information can be used to compute the kinetic energy of the object. This requires an online estimation of the velocity of the object at every sample instant during the capture. Assuming that the object and capture system are completely coupled, the velocity of the end effector can be computed in real-time using forward kinematics from the joint-angles.

3.4 Self-tuning the bell-shaped stiffness control curve

The area under the bell-shaped stiffness curve determines the total work done. In order to decelerate

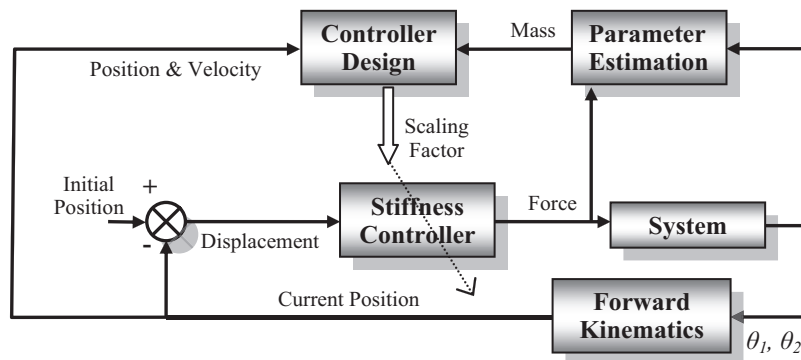


Fig. 6 Block diagram of adaptive bell-shaped stiffness control

the body to a complete stop, the work done must equal the total kinetic energy of the object. If the kinetic energy of the object is known at the time of capture, the parameters that control the stiffness relationship can be designed beforehand so that the area under the resulting bell curve is equal to the kinetic energy of the object.

As discussed earlier, the cosine function given by equation (3) has the required shape for the stiffness response. Since the original area under the bell curve is known from equation (5), the remaining area under the bell curve from the current position can be obtained by subtracting the cumulative area up to the current position X using equation (13)

$$\text{Cumulative Area} = \frac{A}{2} \left[1 + \frac{X - u}{s} + \frac{1}{\pi} \sin \left(\frac{X - u}{s} \pi \right) \right] \quad (13)$$

The principles of work done and energy can then be used to determine if the capture is possible, i.e. the remaining area under the curve is compared with the remaining kinetic energy of the object that is computed online.

1. If the remaining area under the curve is less than the kinetic energy of the object, the capture will fail since the object will not be stopped over the predefined distance.
2. If the remaining area under the curve is greater than the kinetic energy of the object, the capture will fail since the object will be stopped prior to the predefined distance, resulting in jerk due to sudden removal of force.

For successful capture, the remaining area under the curve must be equal to the kinetic energy of the object at every sample instant. This requires that the bell curve be scaled in real-time depending on the kinetic energy of the object. The ratio of the current kinetic energy of the object to the remaining area

under the curve at every sample instant produces the scaling factor γ required to adaptively vary the stiffness relationship

$$\gamma(t) = \frac{M\dot{X}(t)^2}{A\{1 - \{1 + \{[X(t) - u]/s\} + (1/\pi) \sin\{[X(t) - u]/s\}\pi\}\}} \quad (14)$$

where $X(t)$ represents the position of the object and $\dot{X}(t)$ is the velocity at instant t . Equation (13) gives the area up to a specific point in terms of the object's current position X . The area that remains after subtracting this from the total area under the curve is then factored into equation (14) while re-designing the controller. Equation (14) results in a scaling factor γ which must be incorporated into equation (5) so that

$$F(t) = \gamma \left\{ \frac{A}{2s} \left\{ 1 + \cos \left[\frac{X(t) - u}{s} \pi \right] \right\} \right\} \quad (15)$$

Figure 6 shows the block diagram of the adaptive bell-shaped stiffness control scheme. The control scheme of the adaptive bell-shaped stiffness control with respect to the dynamic mass capture can be summarized as follows.

1. The displacement of the end effector on contact with the object causes the application of a force governed by the stiffness relationship.
2. The mass of the object is estimated from the input-output samples which are the forces and accelerations.
3. The velocity of the object is obtained from the end effector movement.
4. Hence, the kinetic energy of the object is computed during the capture.
5. The remaining area under the bell-shaped curve is computed from the current position of the end effector.

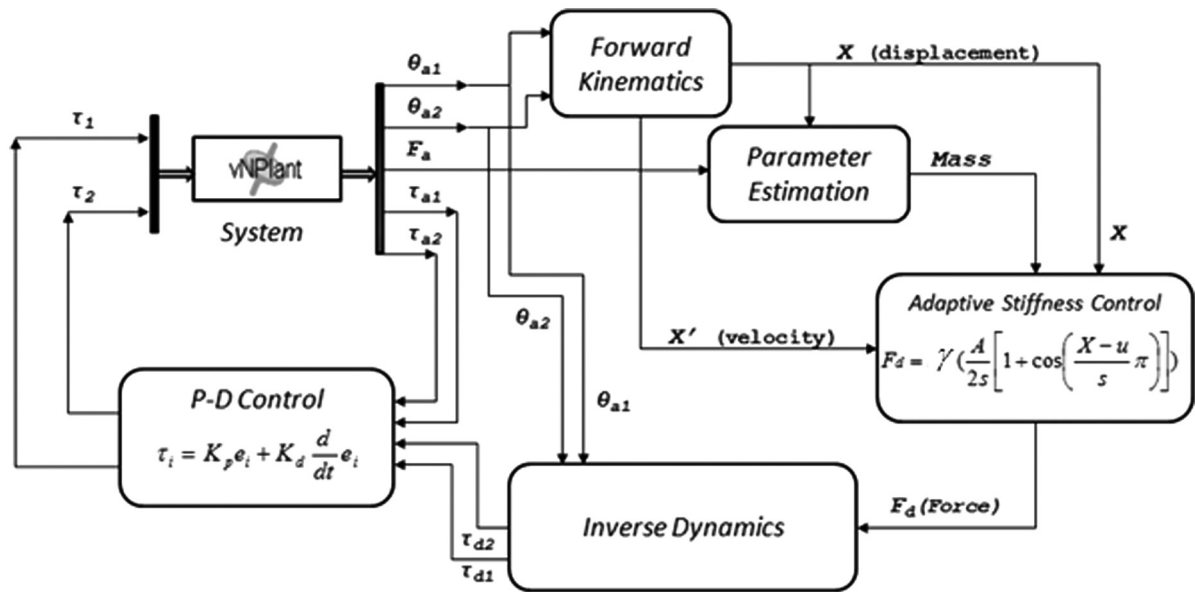


Fig. 7 Adaptive stiffness controller: block diagram

6. The scaling factor obtained from equation (14) is then used to redesign the controller and implement it in real-time according to equation (15).

3.5 Mathematical formulation and implementation for the two-link manipulator

The non-linear stiffness relationship required at the end effector during capture is a result of the dynamic interaction between force and position of the end effector. It is assumed that the links of the manipulator are not flexible. The torques at the link joints are influenced by the model parameters such as link lengths and their mass. The objective is to design the torque control inputs $\tau_1(t)$ and $\tau_2(t)$ such that the end effector applies a force that tracks the desired stiffness relationship, i.e. to ensure that the adaptive bell-shaped position–force profile is accurately implemented. The measurable signals are the joint positions $\theta_{a1}(t)$, $\theta_{a2}(t)$, end effector force $F_a(t)$, and the joint torques $\tau_{a1}(t)$, $\tau_{a2}(t)$. The controller is implemented at a sampling frequency of 1 kHz in the manner shown in Fig. 7.

The end effector position $(x[k], y[k])$, where k is the sample number, is computed using forward kinematics using equations (16) and (17)

$$x[k] = L_2 \cos\{\theta_{a1}[k] + \theta_{a2}[k]\} + L_1 \{\cos \theta_{a1}[k]\} \quad (16)$$

$$y[k] = L_2 \sin\{\theta_{a1}[k] + \theta_{a2}[k]\} + L_1 \{\sin \theta_{a1}[k]\} \quad (17)$$

Contact with the object being captured causes a change (displacement) in the end effector position

$X[k] = (x[k], y[k])$ from its initial position $X_0[k] = (x_0[k], y_0[k])$ and generates torques at the joints which are non-linear in nature due to coupling effects. The stiffness relationship equation outputs a desired force at the end effector in response to this change in position according to equation (15). The desired torques $\tau_{d1}[k]$ and $\tau_{d2}[k]$ to produce this force at the end effector are computed using inverse dynamics (recursive Newton–Euler) according to equation (2).

Closed-loop PD control is used to minimize the error e_i in the joint i torque, so that the control torque τ_i for joint i can be computed

$$e_i = \tau_{di}[k] - \tau_{ai}[k] \quad (18)$$

$$\tau_i[k] = K_p e_i[k] + K_d \frac{d}{dt} e_i[k] \quad (19)$$

with controller gains K_p and K_d appropriately chosen using the Ziegler–Nichols method. The measured force at the end effector during capture $F_a[k]$ and displacement $X[k]$ are passed as inputs to the parameter estimation component, which in turn estimates the mass according to the steps described in section 3.2. The estimated mass and velocity of the end effector (using forward kinematics) are used to compute the estimated kinetic energy of the object being captured, and this estimate is passed to the adaptive stiffness control block, which recomputes the desired force $F_d[k]$ at the end effector according to equation (15). The desired force $F_d[k]$ and the current joint angles $\theta_{a1}[k]$, $\theta_{a2}[k]$ serve as inputs to the inverse dynamics controller which

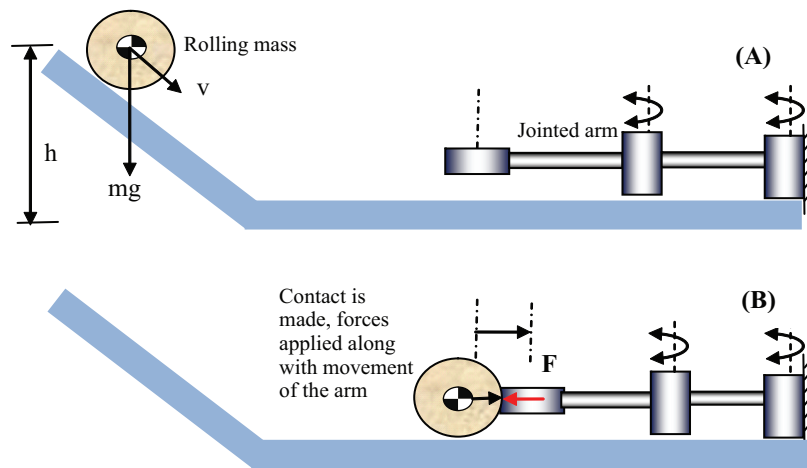


Fig. 8 Decelerating a rolling mass

outputs the desired torques $\tau_{d1}[k]$ and $\tau_{d2}[k]$ to achieve the required non-linear stiffness that ensures minimum jerk during the capture.

4 EXPERIMENTAL RESULTS – STIFFNESS CONTROL

A simplified experimental procedure was used (Fig. 8) to verify the effectiveness of the developed control scheme in capturing a free-moving mass. A relatively large mass was used to maximize the kinetic energy of the object, while keeping its velocity within the bounds of the capture, system actuator performance, and controller hardware. Figure 8(a) illustrates the mass before release, raised to a height, h , above the capture hardware. When released, the cylindrical mass rolled down the ramp and gained initial velocity. The mass then rolled along the flat surface towards the capture system. In Fig. 8(b) the mass has contacted the capture system and is experiencing deceleration forces based upon the controller algorithm. Several assumptions were made in the experimental system.

1. There is no slippage during the rolling, and the effects of friction are negligible over the short distance. This is assumed to be a reasonable depiction of a free-moving capture scenario, without having to deal with a complicated experimental setup that is required to accurately launch the mass at the end effector in free space or integrate sensors to predict and intercept the object, which is beyond the scope of this work.
2. The physics of the rolling mass are taken into account during the capture process.

3. No gripper was used at the end effector, but a soft spongy material is used to line the outside such that lateral movement on impact was minimized. This also compensates for the velocity mismatch on contact.

The experimental hardware consisted of a two-joint serial link manipulator, designed to have two degrees of freedom (Fig. 9(a)). Each joint of the manipulator has DC brushed motors with a gearbox ratio of 1:157, in parallel with potentiometers to measure position and torque sensors to measure applied torque. The motors were chosen to produce a maximum torque output of 1 N m and be capable of the required rotational velocities. Electric motors were ideal for testing the controller performance as their characteristics are well understood and they are relatively inexpensive. However, the torque and velocity capabilities of electric motors make them unsuitable for the majority of capture tasks. Actuator technologies, such as pneumatic or elastic-stored energy, provide far superior power-to-weight characteristics, but are far less understood and their non-linear characteristics make them difficult to control.

A cylindrical mass with a plastic/metal bracket (shown in Fig. 9(b)) was rolled down a ramp and onto a smooth flat surface towards the end effector of the manipulator. A laser sensor was used to measure the position of the mass. A force sensor was attached to the mass, using the metal plate as shown (Fig. 9(a)), to measure the impact with the end effector. The manipulator was required to apply a force to bring the mass to rest over a pre-defined distance. It can be shown that the total kinetic energy KE of a rolling mass is given by equation (20), which is the sum of its rotational and translational energy

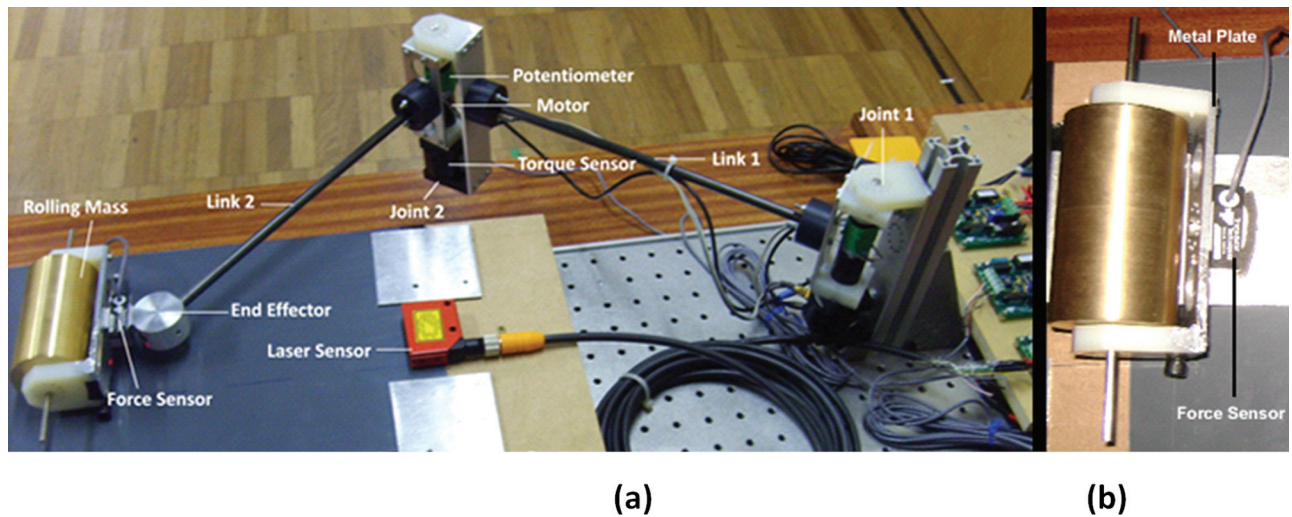


Fig. 9 Experimental setup during bell-shaped stiffness control for capture along single axis: (a) overall rig and (b) close-up view of rolling mass

$$KE = \frac{1}{2} M \dot{X}^2 + \frac{1}{2} I \omega^2 \quad (20)$$

where M is the object's mass, $\dot{X}$ is the linear velocity of the object, I is the object's rotational inertia, and ω is the angular velocity of the object.

It must be noted that equation (20) holds only when an assumption is made that rolling occurs without slipping. If the angular velocity ω of a rotating object with radius R is such that $R\omega$ is the same as the linear velocity $\dot{X}$ of the centre of mass, the object is assumed to be rolling without any slippage. For rolling without slipping, $\omega = \dot{X}/R$. The velocity of the rolling mass (cylinder) at the end of a ramp of length D inclined at an angle Φ can be computed using equation (21)

$$\dot{X} = \sqrt{2D(g \sin(\Phi)/1.5)} \quad (21)$$

where g is the gravitational acceleration. Since the mass travels a small distance after leaving the ramp and before reaching the end effector, its velocity can be assumed to be a constant over this period. Based on the mass and the velocity at the time of leaving the ramp, its kinetic energy can be computed using equation (20). It can also be shown that by applying a force at a height of $0.5R$ above the centre of mass of the cylinder, it can be brought to rest without any slippage.

Proportional feedback control was implemented using torque sensors mounted at the joints to achieve closed-loop torque control. Given that the measured torque from the sensors was T_m and the desired torque was T_d , the applied control signal (voltage) was computed as $V_{in} = K_p(T_d - T_m)$, since

under blocked conditions, it can be assumed that voltage is proportional to the torque.

Figure 10 illustrates the torque tracking of separate joints under blocked conditions (fixed position, measuring the force). Since this is a blocked force, coupling effects are absent and hence the manipulator model has no influence on the response. The system gain is well matched; however, gearbox (ratio 1:157) friction effects cause both stick slip friction at the peaks of the chirp signal and lags in the response. The chirp signal was chosen to be tracked to accentuate this effect as a worst case scenario. This is an unavoidable feature of geared motors that can be successfully minimized through the use of friction compensation algorithms [22, 23].

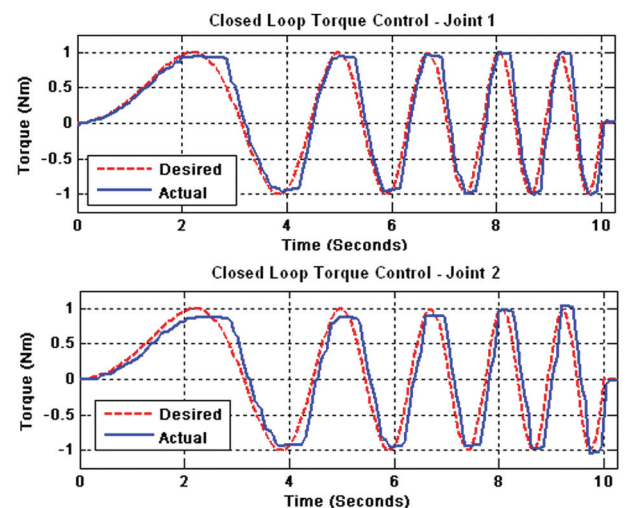


Fig. 10 Performance of closed-loop torque control on both joints

Inverse dynamics was then used to generate the torques required to produce the desired force at the end effector and the bell-shaped stiffness control for dynamic mass capture was implemented. The recursive Newton–Euler (RNE) method was used to compute the inverse dynamics of the system. It must be noted that any errors in the estimation of the model parameters will result in wrongly calculating the joint torques (RNE method) during dynamic interaction which can result in instability of the system.

4.1 Computing the bell-shaped stiffness relationship

In this experiment, the bell-shaped stiffness relationship was implemented along the global X-axis; however, this can be extended to include other axes. The motion of the rolling mass was assumed to be linear (constant velocity) in the plane along the global X-axis due to a slightly sloped approach ramp to compensate for friction. Table 1 shows the calculated parameters of the experimental setup and the kinetic energy of the rolling mass from equations (20) and (21).

The distance over which the mass is expected to be decelerated was chosen to be 0.1 m. The end effector was expected to apply a bell-shaped force to bring the rolling mass to rest over this predefined distance. The bell-shaped stiffness relationship for mass capture is defined by equation (22) [19], where the desired values are chosen from Table 1

$$F = \frac{0.0706}{0.1} \left[1 + \cos \left(\frac{X - 0.05}{0.05} \pi \right) \right] \quad (22)$$

4.2 Deceleration without self-tuning

An experiment was performed where the mass was released with the kinetic energy and stiffness relationship as defined in section 4.1. The mass touched the capture arm resulting in a change in torque and position. The arm then applied forces to the object

Table 1 Parameters of the experimental setup

Parameter	Value
Mass (M)	1.651 kg
Radius (R)	0.025 m
Inertia of cylinder (I) ($0.5 MR^2$)	$5.1594 \times 10^{-4} \text{ kg m}^2$
Length of ramp (D)	0.05 m
Inclination of ramp (ϕ)	0.0873 rad
Velocity of mass ($\dot{X}$)	0.24 m/s
Kinetic energy (KE)	0.0706 J
Link 1 and 2 length	0.1 and 0.1 m

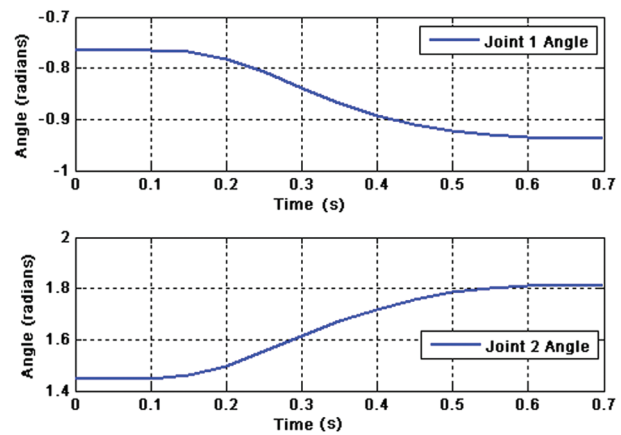


Fig. 11 Joint angles during dynamic mass capture

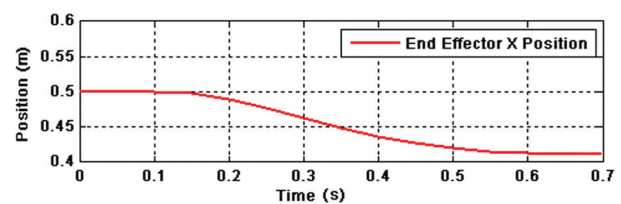


Fig. 12 Position of end effector during the dynamic mass capture

based upon the predefined stiffness relationship using kinematics and inverse dynamics.

Figure 11 shows the joint angles of the two links of the manipulator for the capture, while Fig. 12 shows the graph of the x -position of the end effector in Cartesian space during the capture. The y -position of the end effector is controlled to be a straight line stabilized in the zero position.

From Fig. 12, it is evident that the end effector begins moving after 0.1 s. This is when contact occurs with the rolling mass. The end effector travels nearly 0.1 m, before coming to rest. The rolling mass pushes against the end effector while the actuators at the two joints apply torques to produce the desired force at the end effector to bring the mass to rest. A small amount of residual force is seen when examining the force applied by the end effector (Fig. 13) which indicates friction effects within the system and possible errors in the kinetic energy estimate.

Figure 14 shows the ideal stiffness curve computed from equation (5), target values at the measured discretized positions, and the force demand which is computed experimentally in real time from the end effector displacement. This is a model-based comparison of the system for a single gain, since the desired force being computed in real time

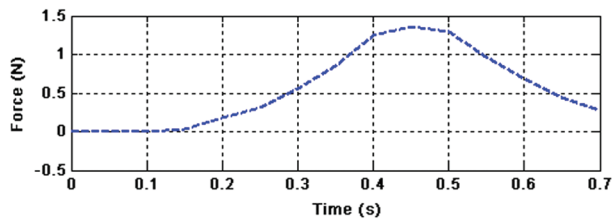


Fig. 13 Actual force applied during the capture

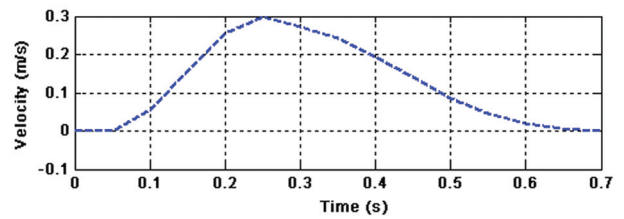


Fig. 16 Velocity of the end effector versus time during the capture

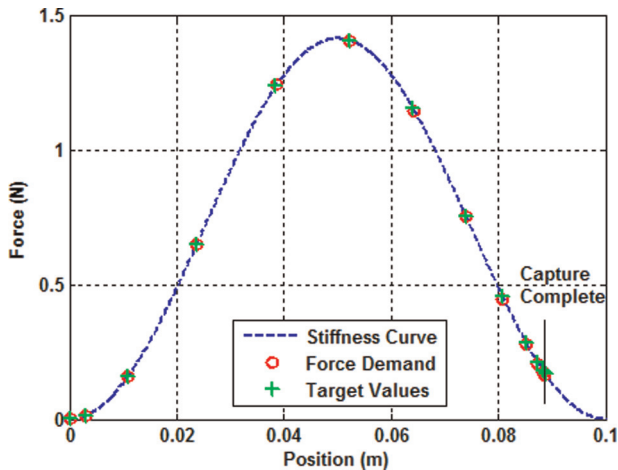


Fig. 14 Comparison of theoretical and experimental stiffness relationships

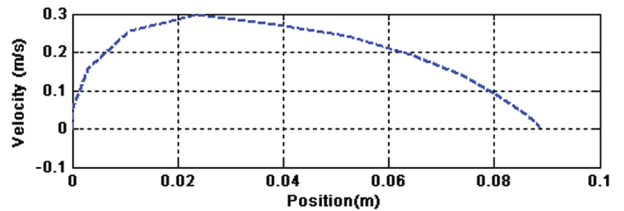


Fig. 17 Velocity of the end effector versus position during the capture

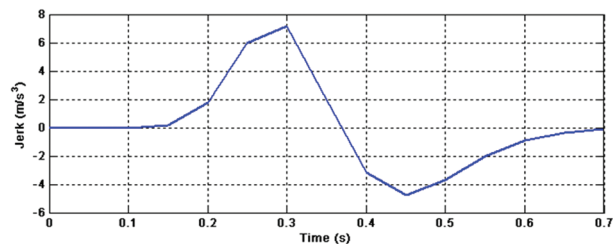


Fig. 15 Jerk experienced during the capture

is directly dependent on the entire manipulator model. There is a 5.5 per cent error in accuracy of the stiffness implementation, which is in keeping with the desired specification. The result from Fig. 14 verifies that:

- the proposed stiffness controller can be accurately implemented using inverse dynamics;
- the forward kinematic model provides a fairly accurate measure of the displacement of the end effector, since the desired stiffness from experiment closely follows the ideal theoretical stiffness.

Figure 15 shows the measured jerk (as calculated from the applied forces) and shows a low peak jerk

profile. Note that the initial impact of the mass with the capture system will not be recorded by the data acquisition hardware due to its short duration. However, this peak is due to a velocity mismatch, and not the deceleration strategy, and will be relatively small due to the low impact velocity (<0.5 m/s).

To verify that the force applied by the end effector brings the object to rest, graphs of the velocity of the end effector against time and position are plotted in Fig. 16 and Fig. 17, respectively. Since the object is in contact with the end effector, the velocities of the two bodies can be treated as being the same.

From Fig. 16, it is clear that the velocity of the object is imparted to the end effector initially. Following this initial period of 0.25 s, the velocity of the end effector gradually decreases to 0 m/s, at which point the object is brought to rest. By observing the velocity graphs, it can be seen that the velocity reduces to 0 m/s in about 0.7 s and the object is brought to rest over a distance of 0.09 m instead of 0.1 m (Fig. 17). This achieves the target goal of stopping an object within 50 per cent of the available linear displacement in the workspace, while keeping the level of jerk experienced to less than 10 m/s^3 . Adaptive control to compensate for errors in estimation of kinetic energy will enable an object to be brought to rest over the precise predetermined distance irrespective of its kinetic energy.

4.3 Simulation results – adaptive stiffness control

The hardware setup is not capable of decelerating quickly moving objects or recording short-duration

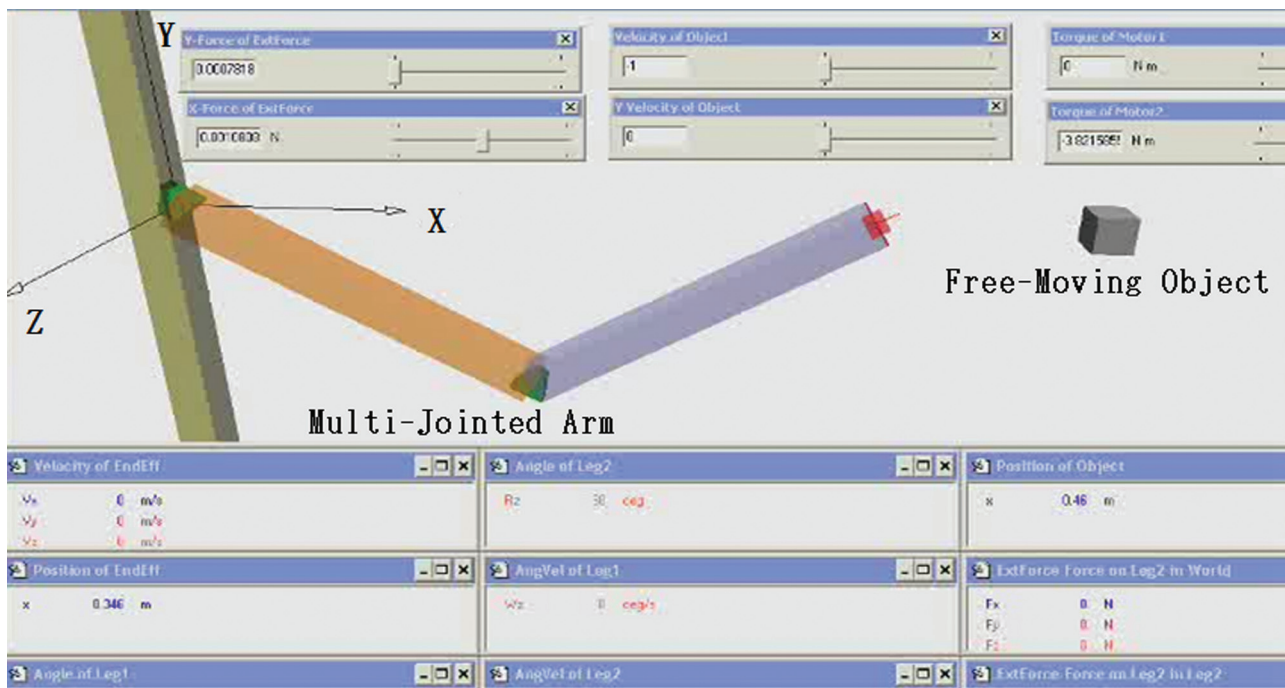


Fig. 18 The Nastran simulation model

parameters such as impact spikes. A simulated environment allows the controller algorithms to be tested in a wider range of scenarios and measure all parameters of the capture. Specifically, it allows the testing of the controller potential when not limited by specific actuator types and hardware.

The simulation was performed by building a dynamic model of the system in Visual Nastran 4D, and interfacing it with Simulink. The Visual Nastran 4D model is illustrated in Fig. 18.

For a given mass and approach velocity, impact frequency can be computed knowing the initial distance over which contact occurs – this serves as a metric to determine the sampling frequency to capture the impact spike in simulation. The adaptive bell-shaped stiffness control was implemented at 1 kHz taking this into account, and used to decelerate the object over a predefined distance when the mass of the object as well as its approach velocity were wrongly estimated: a 3 kg mass was initially estimated to be 4 kg (25 per cent error) and the velocity of 1 m/s was initially estimated at 1.1 m/s. The adaptive bell-shaped stiffness controller was used to capture the object over a predefined distance of 0.2 m. The initial kinetic energy estimate of the object was $(0.5 \times 4 \times 1.1^2) = 2.42$ J.

This value is much higher in simulation due to both the increased velocity of the object and its mass in comparison with the experimental case, where the energy was kept low to enable the actuators to apply the desired force. In simulation, however, the

actuators are capable of producing the desired force to bring this object to rest, and this allows for a large variation in estimated masses and velocities to test the controller performance. Figure 19(a) reveals that the online estimation of kinetic energy during the process of capture helps to scale the bell curve to apply a lesser force than originally designed, so that an object with a lower kinetic energy is still captured over the same predefined stopping distance of 0.2 m. Figure 19(b) shows the difference between the expected initial estimate of the kinetic energy and its

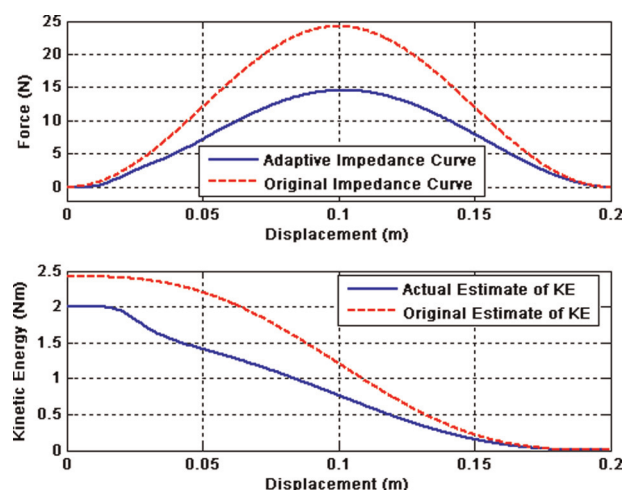


Fig. 19 (a) Adaptive stiffness control using estimated kinetic energy and (b) original and actual estimates of kinetic energy

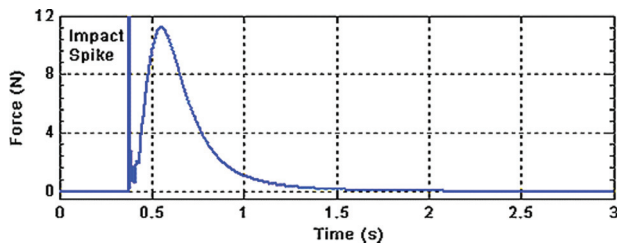


Fig. 20 Force applied during capture in simulation

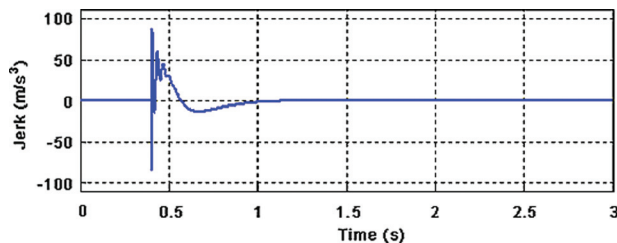


Fig. 21 Jerk experienced during capture in simulation

actual online estimate. It can be seen that the kinetic energy of the mass is reduced to zero over the distance of 0.2 m as expected. The results confirm that the process of parameter estimation – using self-tuning to determine the mass of the object being captured and online velocity estimation from the movement of the end effector during the capture – can be used to successfully capture any object over a chosen stopping distance.

Figures 20 and 21 show the force applied to the object during the capture process and the applied jerk. The first contact between the object and the capture system results in an impact spike, due to velocity mismatch (ideally there would be a pre-capture stage where the velocities are very closely matched). Following the initial impact spike, the force profile becomes smooth. The peak jerk occurs during the impact phase; the peak jerk then reduces to small values. Again, simulation results confirm that the object is brought to rest within 50 percent of the available linear displacement, while keeping the jerk to a minimum during the capture, although the initial impact results in a jerk spike – this can be mitigated using pre-capture velocity matching. Stability of the controller arises from the selected joint space PD gains and the accuracy of the RNE inverse dynamics. This is not unique to this algorithm and is considered in other work [24].

5 CONCLUSIONS

The mass and velocity of a free-moving object determine its kinetic energy and this energy must be

dissipated to bring the object to rest. A method to capture free-moving objects, while ensuring minimum amounts of jerk, is proposed. Experimental results have demonstrated that errors in estimates of the object being captured and end effector dynamics are likely to impair the quality of the capture. To cope with this, a self-tuning approach is proposed, which allows for these inaccuracies to be handled. Continuously estimating the kinetic energy of the object during the capture provides the controller with sufficient information to be able to vary the amount of force being applied in real time to decelerate the object, therefore enabling a successful deceleration over a predefined capture distance within the manipulator workspace. Additionally, the nature of the force being applied ensures minimal damage to both the manipulator and the object, making it suitable for delicate catching tasks.

The experimental equipment was limited in the speed at which it could move and the sample time that could be implemented. However, it successfully enabled testing of the control algorithms for limited values of mass and velocity – requiring a relatively slow-moving object be decelerated. The simulation approach demonstrated the performance of the self-tuning algorithm and revealed impact spikes that cannot be measured on the experimental hardware. Implementation of a velocity matching scenario would minimize the initial impact.

In future work, it is planned to experimentally implement stiffness control independently along each axis. This would permit indirectly regulating the capture trajectories through varied deceleration along multiple axes simultaneously, thus opening up possibilities for guiding the object to a well-defined location during the capture without explicit position control. Future work will also include the use of dedicated hardware and ballistic actuators based around the concept of stored elastic energy.

© Authors 2011

REFERENCES

- 1 Riley, M. and Atkeson, C. G. Robot catching: towards engaging human-humanoid interaction. *Auton. Robots*, 2002, **12**(1), 119–128.
- 2 Burrige, R. R., Rizzi, A. A., and Koditschek, D. E. Toward a dynamical pick and place. In *Proceedings of the IEEE/RSJ International Conference on Intelligent robots and systems*, Pittsburgh, Pennsylvania, USA, 5–9 August 1995, Vol. 2, pp. 292–297.
- 3 Sakaguchi, T., Masutani, Y., and Miyazaki, F. A study on juggling tasks. In *Proceedings of the IEEE/RSJ International Conference on Intelligent*

- robots and systems, Osaka, Japan, 3–5 November 1991, pp. 1418–1423.
- 4 **Buehler, M., Koditschek, D. E., and Kindlmann, P. J.** Planning and control of robotic juggling and catching tasks. *Int. J. Robot. Res.*, 1994, **13**(2), 101–108.
 - 5 **Chapnik, B., Heppler, G., and Aplevich, J.** Modeling impact on a one-link flexible robotic arm. *IEEE Trans. Robot. Autom.*, 1991, **7**, 479–488.
 - 6 **Chapnik, B. V., Heppler, G. R., and Aplevich, J. D.** Controlling the impact response of a one-link flexible robotic arm. *IEEE Trans. Robot. Autom.*, 1993, **9**(3), 346–351.
 - 7 **Rhody, B. J. and Heppler, G. R.** Controlling the dynamics of mass capture by a single flexible link. In Proceedings of the IEEE International Conference on *Robotics and automation*, Atlanta, Georgia, USA, 2–6 May 1993, pp. 496–501.
 - 8 **Buttazzo, G. C., Allotta, B., and Fanizza, F. P.** Mousebuster: a robot for real-time catching. *IEEE Control Syst. Mag.*, 1994, **14**(1), 49–56.
 - 9 **Kajikawa, S., Saito, M., Ohba, K., and Inooka, H.** Analysis of human arm movement for catching a moving object. In Proceedings of the IEEE International Conference on *Systems, man, and cybernetics*, Tokyo, Japan, 12–15 October 1999, vol. 2, pp. 698–703.
 - 10 **Kövecses, J., Cleghorn, W. L., and Fenton, R. G.** Dynamic modeling and analysis of a robot manipulator intercepting and capturing a moving object, with the consideration of structural flexibility. *Multibody Syst. Dyn.*, 1999, **3**(2), 137–162.
 - 11 **Lin, Z., Zeman, V., and Patel, R. V.** On-line robot trajectory planning for catching a moving object. In Proceedings of the IEEE International Conference on *Robotics and automation*, Scottsdale, Arizona, USA, 14–19 May 1989, pp. 1726–1731.
 - 12 **Muenchhof, M. and Singh, T.** Desensitized jerk limited-time optimal control of multi-input systems. *J. Guid. Control Dyn.*, 2002, **25**(3), 474–481.
 - 13 **Barre, J., Bearee, R., Borne, P., and Dumetz, E.** Influence of a jerk controlled movement law on the vibratory behaviour of high-dynamics systems. *J. Intell. Robot. Syst.*, 2005, **42**, 275–293.
 - 14 **Kyriakopoulos, K. J. and Saridis, G. N.** Minimum-jerk path generation. In Proceedings of the IEEE International Conference on *Robotics and automation*, Philadelphia, Pennsylvania, USA, 24–29 April 1988, pp. 364–369.
 - 15 **Huang, P., Xu, Y., and Liang, B.** Global minimum-jerk trajectory planning of space manipulator. *Int. J. Control Autom. Syst.*, 2006, **4**(4), 405–413.
 - 16 **Macfarlane, S. and Croft, E. A.** Jerk-bounded manipulator trajectory planning: design for real-time applications. *IEEE Trans. Robot. Autom.*, 2003, **19**(1), 42–52.
 - 17 **Raibert, M. H. and Craig, J. J.** Hybrid position/force control of manipulators. *Trans. ASME, J. Dyn. Syst. Meas. Control*, 1981, **102**, 126–133.
 - 18 **Hogan, N.** Impedance control: an approach to manipulation: parts I, II, III. *Trans. ASME, J. Dyn. Syst. Meas. Control*, 1985, **107**, 1–24.
 - 19 **Nagendran, A., Richardson, R. C., and Crowther, W. J.** Bell shaped impedance control to minimize jerk while capturing delicate moving objects. ICINCO-RA (2): 2007. In Proceedings of the Fourth International Conference on *Informatics in Control, automation and robotics, robotics and automation 2*, Angers, France, 9–12 May 2007, pp. 504–511.
 - 20 **Kazerooni, H.** Robust, non-linear impedance control for robot manipulators. In Proceedings of the IEEE International Conference on *Robotics and automation*, Raleigh, North Carolina, 31 March–3 April 1987, pp. 741–750.
 - 21 **Hayes and Monson, H.** Recursive least squares. In *Statistical digital signal processing and modeling*, 1996, ch. 9.4, p. 541 (Wiley, New York).
 - 22 **Canudas, C., Astrom, K., and Braun, K.** Adaptive friction compensation in DC-motor drives. *IEEE Trans. Robot. Autom.*, 2002, **3**(6), 681–685.
 - 23 **Teeter, J. T., Chow, M., and Brickley Jr, J. J.** A novel fuzzy friction compensation approach to improve the performance of a DC motor control system. *IEEE Trans. Ind. Electron.*, 2002, **43**(1), 113–120.
 - 24 **Oaki, J. and Adachi, S.** Decoupling identification for serial two-link robot arm with elastic joints. In Proceedings of the 15th IFAC Symposium on *System identification*, Saint-Malo, France, 6–8 July 2009, pp. 1417–1422.

APPENDIX

Notation

a_0	plant coefficient
A	gain for self-tuning
$A(z^{-1})$	plant model polynomial
b_0	plant coefficient
$B(z^{-1})$	plant model polynomials
C	damping coefficient (N s/m)
D	length of experimental ramp (m)
F	force applied to decelerate mass (N)
g	acceleration due to gravity (m/s ²)
I	moment of inertia (kg m ²)
$\hat{J}$	non-dimensional jerk
k_t	parameter change gain
K	spring constant (N/m)
KE	kinetic energy (J)
m	order of plant polynomials
M	mass of object (kg)
n	order of plant polynomials
P_t	tuning gain
q_t	plant output sample at time t
R	radius of rolling object (m)
s	bell-shaped stiffness controller parameter
t, T	time (s)

u	bell-shaped stiffness controller parameters	θ	angle (rad)
u_i	input data	$\boldsymbol{\theta}$	parameter vector
X	linear displacement (m)	$\dot{\boldsymbol{\theta}}$	angular velocity (rad/s)
$\dot{X}$	velocity (m/s)	$\ddot{\boldsymbol{\theta}}$	angular acceleration (rad/s ²)
$\ddot{X}$	acceleration (m/s ²)	$\hat{\boldsymbol{\theta}}_t$	parameter vector estimate
X_0	equilibrium position (m)	$\boldsymbol{\tau}$	actuator torque (N m)
$\mathbf{y}$	output vector	Φ	inclination of experimental ramp (rad)
y_t	plant input sample at time t	$\boldsymbol{\psi}$	regressor matrix
γ	scaling factor applied during stiffness control	ω	angular velocity of rolling mass (rad/s)
$\zeta = c/2\sqrt{km}$	damping ratio	$\boldsymbol{\omega}_t$	regressor vector