Swing-up Regrasping Algorithm using Energy Control

Avishai Sintov and Amir Shapiro

***Abstract*— In this paper we propose an energy control based algorithm for performing swing-up regrasping. In such regrasping motion, an object is manipulated using a robotic arm around a point pinched by the arms gripper. The aim is to manipulate the object from an initial angle to regrasp it on a new desired angle relative to the gripper. The pinching point function as a semi-active joint where the gripper is able to apply only dissipative frictional torques on the object to resist its motion. We address the problem by proposing an algorithm based on energy control. Simulations on a three degrees of freedom manipulator regrasping a bar validate the proposed algorithm.**

I. Introduction

Regrasping is an operation for alternating grasp configurations of the object with respect to the task to be done. Current regrasping methodologies work only with highly redundant (and hence expensive) hand architectures, and require overly sophisticated sensory feedback. In the robotics literature, there are three known approaches for regrasping. The first approach is picking and placing where the object is put on a surface and picked up again in a different grasp configuration [1], [2]. The pick and place approach is rather slow and demands a large surface area around the robot. The second approach is the use of the grippers degrees of freedom to move between contact points while maintaining a force-closure grasp during the entire process [3]–[8]. This approach is also called *quasi-static finger gaiting* in the robotics literature. However, quasi-static finger gaiting is quite wasteful, as it requires sufficiently many degrees of freedom (requiring highly redundant finger linkages) to manipulate the grasped object between two grasp configurations while maintaining force closure grasps. The third approach is much faster and efficient, however more complex, as it uses dynamical manipulations to switch between grasp configurations. The gripper allows relative velocity with respect to the object by releasing it through a series of dynamic manipulations. It regains fixed contact with the object by catching it at the final pose [9]. Most work done in this field use a multi-fingered highly dexterous hand for performing regrasping. The work in [10] proposed a regrasping strategy based on visual feedback of the manipulated object, this with a multi-fingered hand. In [11] a regrasping method was introduced using a 3-finger hand with no external sensing for feedback.

Our long term goal is to build a library of basic regrasping manipulations that will serve as building blocks for higher task executions. Example applications are dynamic assembly tasks where such manipulations can reduce the number of arms required and speed up the assembly process. In this paper we address a sector of the regrasping problem termed *Swing-up Regrasping*. Human hands perform swing-up regrasping motions to alter the angle between the palm and a grasped object (Figure 1). This is a dynamic manipulation to grant the object with enough energy to reach the desired angle while rotating around a pivot point between the pinching fingers. We aim to mimic the swing-up motion of the human hand. Thus, we propose an algorithm based on energy control which brings the object to the desired angles potential energy. Energy control is used not to stabilize the systems state, but its energy on a desired value [12]–[14]. The energy control is shown to be based on the Lyapunov stability theory.

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Fig. 1. Hand swing-up regrasping from initial angle (left image) to final angle (right image)

An important matter discussed in this paper is the nature of the joint formed at the pinching (pivot) point. The grippers jaws hold the object and enable relative velocity. Thus, torsional friction exists at the pivot and is controlled by the normal force the jaws apply. Therefore, the pivot point is a joint that is only able to resist the motion of the object, i.e., can only dissipate energy. Such joint is termed a *Semi-Active joint* and its notion arises from semi-active friction dampers [15]. We model a semi-active robotic joint and use active control of the normal force applied to the object. We want to prevent the object from slipping due to its inertia but also want to avoid sticking due to an overly high force.

The paper is organized as follows. Section II defines the swing-up regrasping problem. In section III we formulate the dynamics and frictional model. The energy control is presented in Section IV along with the proposed swing-up regrasping algorithm. Section V presents simulations of a three degrees of freedom robotic arm regrasping a bar. Conclusions and future work are discussed in Section VI.

II. Problem definition

Consider an n-joint manipulator dynamics given by

$$M(\mathbf{q})\ddot{\mathbf{q}} + C(\mathbf{q},\dot{\mathbf{q}})\dot{\mathbf{q}} + G(\mathbf{q}) = \mathbf{u_m}, \quad (1)$$

where $\mathbf{q}(t) = [q_1(t) \cdots q_n(t)]^T \in \mathbb{R}^n$ is the vector of joints angles at time t, $\mathbf{u_m}(t) = [u_1(t) \cdots u_n(t)]^T \in \mathbb{R}^n$ is the input torque control vector, M is an $n \times n$ inertia matrix,

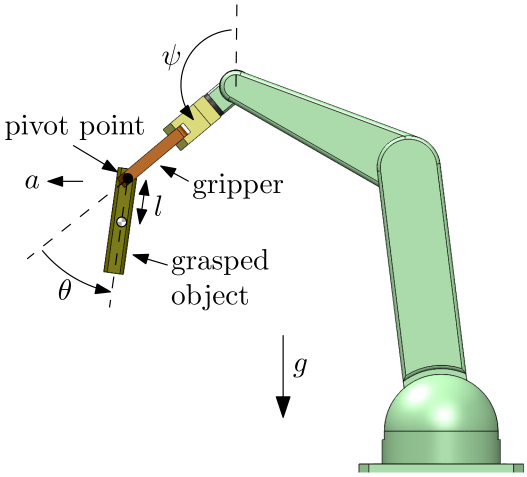

Fig. 2. Object grasped by the robotic arm with angle θ.

C is the $n \times n$ centrifugal and Coriolis matrix, and G is an $n \times 1$ vector of joint torques due to gravitational force. A simple jaw gripper is fixed at the tip of link n. Both jaws of the gripper are parallel such that they can apply parallel and equal forces $f_N \geq 0$ to the grasped object. The grippers pitch angle is denoted by ψ and is measured relative to the vertical axis as seen in Figure 2.

Given object with mass m held by the gripper at the pivot point. Let h be a plane containing link n's axis and parallel to the grippers jaws. Let the moment of inertia of the object be I about the objects Center of Mass (COM) on an axis perpendicular to h. Furthermore, let l be the distance from the pivot to the COM's projection on h. Angle θ is defined to be the angle of the object relative to the gripper, i.e., angle between link n's axis and the axis formed by the COM and the pivot point. Zero angle is defined to be when the object's axis is aligned with the grippers axis and the positive direction is c.c.w as marked in Figure 2 . We assume that the whole regrasping motion is performed such that plane h is vertical and contains the gravity vector g. Figure 2 is an example of such system where h is the robots motion plane.

The regrasping problem is defined as follows. An object is held by the gripper of system (1). Given the initial angle $\theta(t=0) = \theta_o$ between the object and the gripper, perform a manipulation motion such that

$$\lim_{t\to\infty} \theta(t) = \theta_d \text{ and } \lim_{t\to\infty} \dot{\theta}(t) = 0. \tag{2}$$

In other words, the manipulation motion should bring the object to angle θ_d with zero velocity. It should be noted that in this work we give the regrasping method the term *swing-up*. However, the use of the term refers both to swinging up the object and swinging it down where the initial pose has higher potential energy than the goal pose.

III. Model Formulation

A. Object Model

In this work we do not deal with the motion planning of the arm. Hence, we assume its ability to provide acceleration of the gripper/pivot at any direction. Nevertheless, we assume motion of the gripper to perform the regrasping only on the horizontal axis. Moreover, through out the motion, the grippers pitch angle ψ is set to remain constant, i.e., $\dot{\psi} = 0$. These simplify the formulation without loss of generality. Further, we assume that the state (angle θ and angular velocity $\dot{\theta}$), and the physical and dynamic properties I, m, l of the object are fully known. The release of the object by the gripper is assumed to be done fast enough to neglect dynamic effects as well as other external disturbances.

Let $\phi(t) = \theta(t) + \psi$ be the objects absolute angle relative to the vertical axis. In such case, the objects model is equivalent to the inverted pendulum model and is given by

$$(I + ml^2)\ddot{\phi} - mgl \sin\phi + mal \cos\phi = 2\tau \tag{3}$$

where a is the pivot points acceleration on the horizontal axis and τ is the friction torque exerted at each jaw. Therefore, system (3) has two inputs: acceleration a provided by the motion of the arm and friction torque τ defined by the normal force f_N applied by the gripper. The friction model is presented next.

B. Friction model

Friction exists between the jaw gripper and the object at the pivot point. We assume a soft-finger contact model [16] between the jaws and objects surfaces. When there is no relative velocity (i.e., $\dot{\theta} = 0$), the static friction torque τ_s exerted on the pivot is, according to the *Coulomb friction model*,

$$|\tau_s| \leq \gamma f_N \tag{4}$$

where $\gamma > 0$ is the static coefficient of torsional friction. When relative velocity exists, $\dot{\theta} \neq 0$, we use the *Signum-Friction Model* [17] expressing the friction torque as

$$\tau_m = -\nu f_N \text{sgn}(\dot{\theta}) \tag{5}$$

where ν is the dynamic torsional coefficient of friction. Note that τ_m is a dissipative torque and therefore is applied opposite to the direction of motion. For changing velocities where the velocity crosses the $\dot{\theta} = 0$ line, switching between models (4) and (5) lead to numerical difficulties. Karnopp [18] proposed to define a small neighborhood of zero velocity, $|\dot{\theta}| \leq \varepsilon$ for some small $\varepsilon > 0$, where the friction torque τ is equal to the net torque τ_t acting on the object. When the object is with zero velocity, the normal force f_N will be chosen to counter-balance the net torque with $f_N = |\tau_t|/(2\gamma)$. The net torque when the object is with zero relative velocity, e.g., $|\dot{\theta}| \leq \varepsilon$ is given by

$$\tau_t = -mgl \sin\phi - mal \cos\phi. \tag{6}$$

The normal force to be applied when $|\dot{\theta}| > \varepsilon$ will be defined in the next subsection. The overall friction model used in this work defines the friction torque τ with respect to the normal force as

$$\tau(f_N) = \begin{cases} -\gamma f_N \text{sgn}(\tau_t), & |\dot{\theta}| \leq \varepsilon \\ -\nu f_N \text{sgn}(\dot{\theta}), & |\dot{\theta}| > \varepsilon \end{cases} . \tag{7}$$

One may view the system of the arm and object as an under-actuated $(n+1)$-degrees arm with n actuated joints and one semi-actuated joint [19]. A semi-actuated joint enables only to counter-act the motion by controlling the normal force applied at the pivot point. That is, we apply a positive normal force while the resultant friction torque must satisfy the dissipative constraint

$$\tau \cdot \dot{\theta} < 0 \ . \tag{8}$$

The control of such joints impose difficulties as a control torque can not be applied to assist in the direction of motion and it must satisfy (8).

C. Gripper Holding Force

The minimal normal force required to hold the object in the gripper without linear slippage due to inertial force is calculated next. The angular velocity and acceleration vectors of the object are $\dot{\phi}\hat{\mathbf{k}}$ and $\ddot{\phi}\hat{\mathbf{k}}$, respectively. By application of the Newton-Euler method [20], the linear acceleration of the object's COM is

$$\dot{\mathbf{v}}_{\mathbf{l}} = \dot{\mathbf{v}}_{\mathbf{gp}} + \ddot{\phi}\hat{\mathbf{k}} \times \mathbf{l} + \dot{\phi}\hat{\mathbf{k}} \times (\dot{\phi}\hat{\mathbf{k}} \times \mathbf{l}) \tag{9}$$

where $\mathbf{l}$ is the vector from the pivot point to the object's COM. The vector $\mathbf{v}_{\mathbf{gp}}$ is the grippers linear velocity vector given by $\mathbf{v}_{\mathbf{gp}} = J\dot{\mathbf{q}}$ where J is the Jacobian matrix of the arm. We assume a planner motion such that there is no velocity in direction perpendicular to plane h. Consequently, the inertial forces acting on the object's COM are given by

$$\mathbf{F}_{\mathbf{l}} = m\dot{\mathbf{v}}_{\mathbf{l}}. \tag{10}$$

Therefore, the net force which must be resisted at the pivot is $\|\mathbf{F}_{\mathbf{l}}\|$ and the normal force exerted by the gripper must satisfy $\|\mathbf{F}_{\mathbf{l}}\| \leq \mu f_N$ where μ is the linear coefficient of friction. During swinging of the object, we set the normal force to be as minimal as possible, that is,

$$f_N = \frac{1}{\mu}\|\mathbf{F}_{\mathbf{l}}\|. \tag{11}$$

In such case, there will be no linear slippage.

IV. Swing-up Regrapsping

In this section we present the theory of energy control and propose an algorithm for performing the swing-up regrasping.

A. Energy Control

Controlling the object's energy is an efficient way to bring it near the desired goal angle. The idea is to bring the energy of the system to a pure potential energy E_d associated with the desired angle ϕ_d. That will grant the object the required energy to reach the desired angle with zero velocity. We base our controller on the one presented in [14]. The energy of system (3) at any time instant is given by

$$E(\phi, \dot{\phi}) = \frac{1}{2}(I + ml^2)\dot{\phi}^2 + mgl(\cos\phi + 1) \tag{12}$$

where zero energy is defined at the downright position. The energy change is given by the derivative

$$\dot{E} = (I + ml^2)\dot{\phi}\ddot{\phi} - mgl\dot{\phi}sin\phi \tag{13}$$

and by substituting system (3) in (13) we acquire the energy change rate

$$\dot{E} = -mal\dot{\phi}\cos\phi + 2\tau\dot{\phi} \tag{14}$$

The second component in (14) is the energy loss due to friction (negative according to (8)). However, the second component is minor compared to the first component and can be neglected. This was validated in the simulation results. Therefore, the energy change rate is

$$\dot{E} = -mal\dot{\phi}\cos\phi \tag{15}$$

which means that alternating the object's energy could be done using a. That is, we accelerate the pivot using the robotic arm to control the object's energy. Note that controllability is obtained only when $\dot{\phi} \neq 0$. Moreover, to gain positive energy, $a\cos\phi$ must be positive when $\dot{\phi}$ is negative, or vice versa.

We would like to find a control law for a that will give the object energy to reach a desired angle with zero velocity. That is, reach the energy $E_d = E(\phi_d, 0) = mgl(\cos\phi_d + 1)$ which is pure potential energy at angle $\phi_d = \theta_d + \psi$ with zero kinetic energy. Consider the following Lyapunov candidate function [21]

$$V = \frac{1}{2}\left(E - E_d\right)^2 \tag{16}$$

where E is calculated using (12). Substituting (15) to the time derivative of V gives

$$\dot{V} = \left(E - E_d\right)\dot{E} = -mal\dot{\phi}\cos\phi\left(E - E_d\right). \tag{17}$$

By applying a controller of the form

$$a = \Gamma\left(E - E_d\right)\dot{\phi}\cos\phi \tag{18}$$

with some user defined gain $\Gamma > 0$ in (17), we show that

$$\dot{V} = -ml\Gamma\dot{\phi}^2\cos^2\phi\left(E - E_d\right)^2 \leq 0 \ . \tag{19}$$

Therefore, as long as $\dot{\phi} \neq 0$, the Lyapunov function decreases and the systems energy is driven to E_d.

Control law (18) will drive the object to the desired energy E_d. When starting from rest, the velocity is zero and therefore the controller could not be initiated. Hence, we apply initial velocity at time $t = 0$ to the object. Solely releasing the object could be feasible only if the release will move it toward the goal, otherwise the energy control would turn it in the wrong direction. Therefore, we use an impact function

$$a(0) = \delta \cdot g(\phi_o) \tag{20}$$

where $\delta > 0$ is a small user defined value and $g(\phi_o)$ is the direction function given by

$$g(\phi_o) = \begin{cases} 1, & \frac{\pi}{2} < |\phi_0| > \frac{3\pi}{2} \\ -1, & 0 < |\phi_0| < \frac{\pi}{2} \text{ or } \frac{3\pi}{2} < |\phi_0| < \psi + \pi \end{cases} . \tag{21}$$

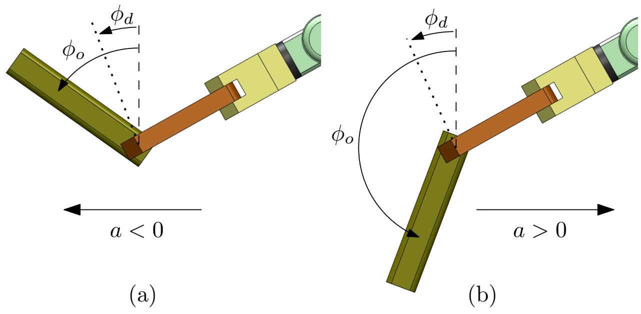

Fig. 3. Two cases that define the sign of the initial impact.

The direction function would initiate motion toward the goal according to the initial pose as illustrated in Figure 3. We have shown stability of controller (18) only in the energy domain, not in the state space. That is, the motion will remain on a manifold in the state space defined by $E(\phi, \dot{\phi}) = E_d$. The object would converge to the desired energy but not to the desired state. Thus, the object would move to the desired goal with constant energy. The ellipse tolerance criterion

$$\|\mathbf{x} - \mathbf{x_d}\|_H^2 \leq \epsilon^2 \quad (22)$$

for some small $\epsilon > 0$, where $\mathbf{x} = (\phi \quad \dot{\phi})^T$ is the current state of the object and $\mathbf{x_d} = (\phi_d \quad 0)^T$ is the desired state, defines a region close enough to the goal. Because the object moves toward the goal, once the whole energy is converted to potential energy, the goal state is reached. At that time instant, when the ellipse tolerance criterion is satisfied, the gripper applies normal force larger then the net torque τ_t, i.e., $f_N > \frac{1}{\gamma}|\tau_t|$ to fix the object at the desired angle.

B. Swing-up regrasp algorithm

The full algorithm for swing-up regrasping from an initial angle θ_o to a goal angle θ_d is presented in Algorithm 1. The first step of the algorithm is the determination of the grippers pitch angle ψ in Line 1, which is, as mentioned, constant through the whole motion. The pitch angle should be chosen based on the motion planning constraints of the arm. However, as we do not deal with the motion planning of the arm, we can only leave the pitch angle as user-defined and impose a constraint on it.

To formulate constraints on the grippers pitch angle, we make a distinction between two cases: swinging-up the object where the desired goal has higher potential energy than the initial pose and the opposite swinging-down situation where the initial angle has higher potential energy. Let the pitch angle be measured within $-180^o < \psi \leq 180^o$ where zero angle is in the upright position. For the first case, the pitch ψ must be chosen such that the two conditions

$$E(\theta_d + \psi, 0) > E(\theta_0 + \psi, 0) \quad (23)$$

and

$$|\psi + \theta_d| \geq \lambda \quad (24)$$

are satisfied for a user-defined angle $\lambda > 0$. Condition (23) defines the swing-up situation while condition (24) prevents the object to reach the upright position $\phi = 0$, flip to the other side and accelerate downwards. In such event it would be difficult to catch it in the right angle. The object will accelerate instead of reaching the desired angle with zero velocity. Therefore, the pitch angle should be chosen such that it is with at least an offset of λ from the zero angle.

In the second case, we transfer the object from a high potential energy angle to a low one. Therefore, the pitch ψ must be chosen such that

$$E(\theta_0 + \psi, 0) > E(\theta_d + \psi, 0) \quad (25)$$

and

$$\text{sgn}(\theta_0 + \psi) \neq \text{sgn}(\theta_d + \psi) \quad (26)$$

are satisfied. Condition (26) ensures that the goal angle could be reached with zero velocity.

Algorithm 1 Swing-up regrasping algorithm

Input: Initial angle - θ_o, goal angle - θ_d.
Output: Motion from initial to goal angles.
1: Select pitch ψ that satisfies (23)-(24) or (25)-(26).
2: Calculate $\phi_o = \theta_o + \psi$ and $\phi_d = \theta_d + \psi$.
3: Select energy controller gain Γ.
4: Select magnitude $\delta > 0$ of initial impact.
5: Apply initial impact $a(0)$ according to (20) for Δt time.
6: **while** $\|\mathbf{x} - \mathbf{x_d}\|_H^2 > \epsilon^2$ **do**
7:     Measure ϕ and $\dot{\phi}$.
8:     Apply controller $a = \Gamma\left(E(\phi, \dot{\phi}) - E_d\right)\dot{\phi}\cos\phi$.
9:     Apply normal force f_N according to (11).
10: **end while**
11: Apply normal force $f_N > \frac{1}{\gamma}|\tau_t|$.
12: Brake arms motion.

After defining the control gain and impact magnitude, we apply an initial impact $a(0)$ as defined in (20) for a small time interval $\Delta t \ll 1$. In lines 6-10 the control energy law (18) is implemented while measuring the objects state to close the control loop. Once the object satisfies the ellipse tolerance constraint (22), the object is fixed by applying high normal force and the arm is stopped.

V. Simulations

Simulations were performed on a three degrees of freedom robotic arm. The properties of a plastic bar object to be regrasped are: $m = 171[g]$, $I = 7.7 \cdot 10^{-5}[kg \cdot m^2]$ and $l = 80[mm]$. Further, the fingertips are assumed to be made of a printed rubber-like polymer. Such material on the plastic bar will provide relatively low torsional friction with high tangential friction against linear slippage. Therefore, the torsional friction coefficient is taken as $\nu = 0.0015$ and the tangential friction coefficient as $\mu = 0.8$.

The aim is to regrasp the bar, initially grasped at angle $\theta_0 = 80^o$, at a goal angle of $\theta_d = -110^o$. The pitch angle was defined to be $\psi = 130^o$. The controller gain was set to $\Gamma = 80$ and with impulse gain of $\delta = 5$ the system was initiated. Figure 4 shows snapshots of the motion to swing-up the bar and regrasp it at the new desired angle.

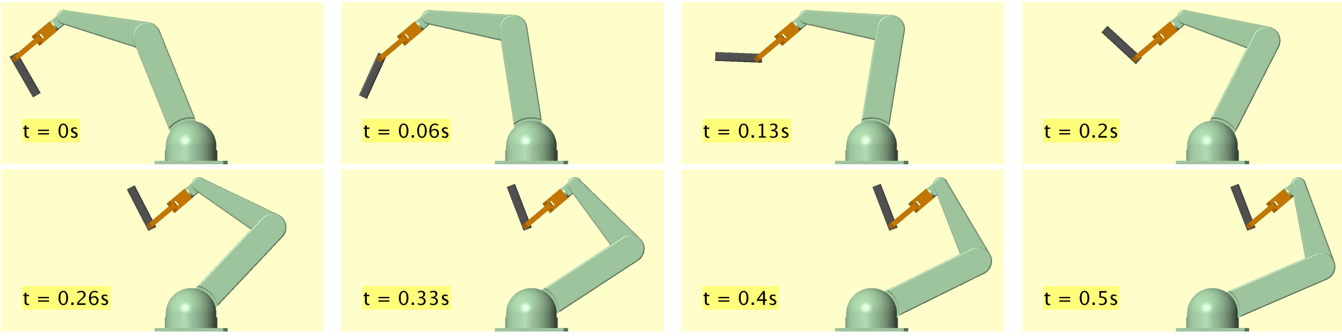

Fig. 4. Simulation of the energy controller performing a swing-up regrasping from $\theta_0 = 80^o$ to $\theta_d = -110^o$.

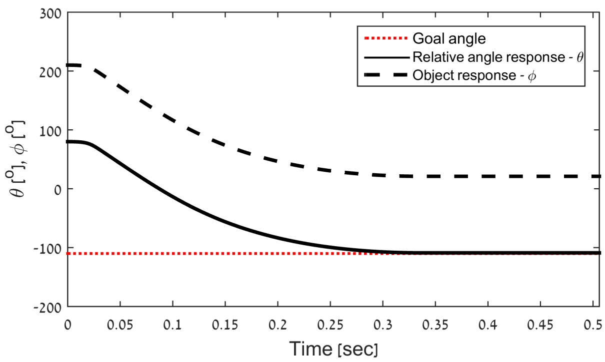

Fig. 5. The object's angle response. The solid curve indicates the angle relative to the gripper while the dashed curve is the angle relative to the vertical.

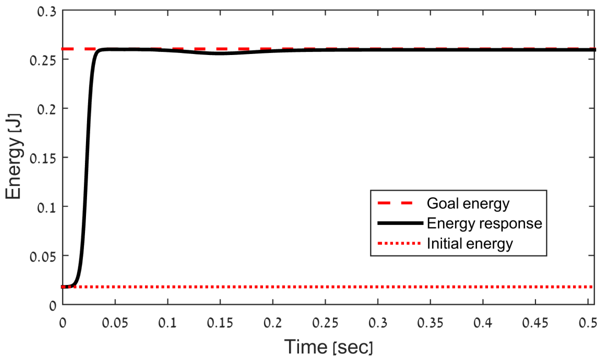

Fig. 6. The object's energy response with the energy controller.

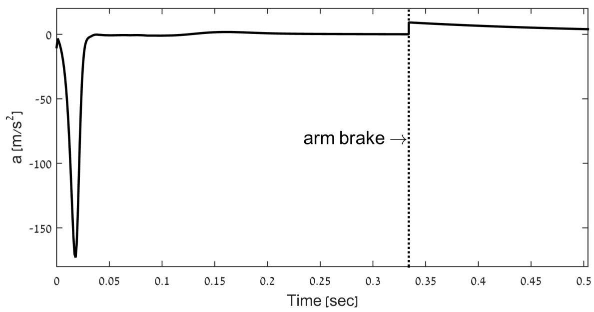

Fig. 7. Acceleration input to the pivot of the object.

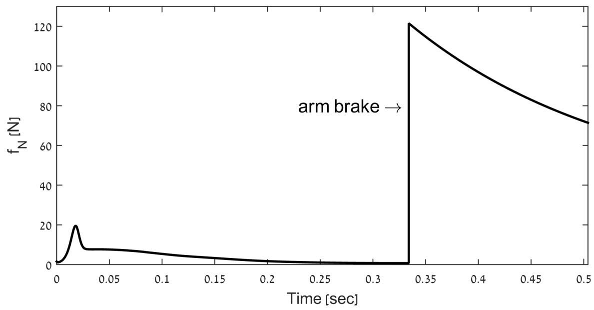

Fig. 8. The normal force input exerted on the object by the gripper.

The angle response can be seen in Figure 5 showing both relative angle $\theta(t)$ and bar angle $\phi(t)$. The bar's angle rapidly converges to the desired angle and at time $t = 0.33s$ the gripper regrasps it while it is in θ_d with zero velocity. In Figure 6 the energy of the bar is seen computed according to (12). The energy rapidly converges to the goal potential energy. However, a small disruption can be seen around time $t = 0.15s$. Around that time, the bars angle is near 90^o which lowers the controllers (18) ability due to the cosine component.

Figures 7-8 illustrate the two inputs to the bar. Figure 7 shows the acceleration a input to the bars pivot. Acceleration a begins with large intensity for swing-up toward the goal and then small values for frictional energy loss corrections. In Figure 8 the normal force applied to the bar is seen to overcome the slippage from the pivot due to inertia. At time $t = 0.33s$ the bar reaches its desired angle and the gripper applies high normal force both to fix the bar and to overcome the high acceleration caused by the braking of the arm. When the arm reaches zero velocity, the gripper applies the required normal force to overcome the torque caused by gravity.

For the case where the initial angle has higher potential energy than the goal, we have simulated a regrasping motion from angle $\theta_0 = -80^o$ to a goal angle of $\theta_d = 110^o$ with the same pitch angle. The angle, acceleration input and energy responses can be seen in Figures 9, 10 and 11, respectively. The gripper first apply positive acceleration to bring the bar toward the goal and than negative acceleration to decelerate the bar to the desired energy.

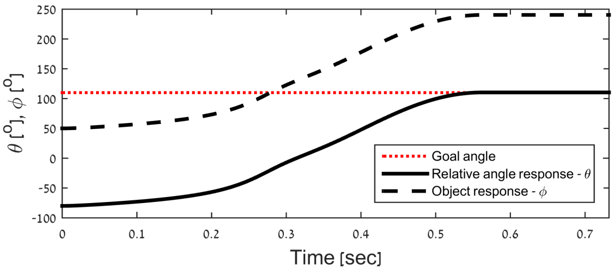

Fig. 9. The object's angle response regrasping from a high energy angle to a low one.

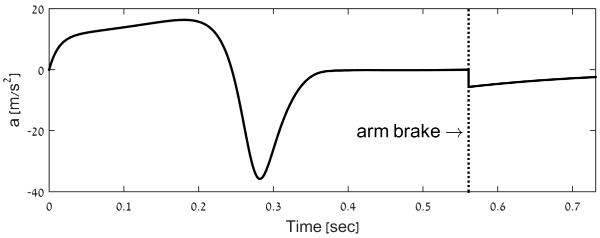

Fig. 10. Acceleration input to the pivot of the object while regrasping from a high energy angle to a low one..

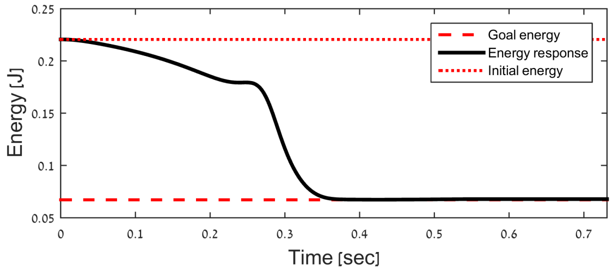

Fig. 11. The object's energy response while regrasping from a high energy angle to a low one.

VI. Conclusions

In this paper we have presented an algorithm for performing swing-up regrasping. We proposed an energy control approach which can grant the object with the necessary energy to reach the desired energy. Thus, the object will reach the desired angle with zero velocity. We have shown that this approach is stable in the energy domain. Simulations on a three degrees of freedom arm regrasping a plastic bar were presented to validate the proposed approaches.

In this energy control approach, an accurate final grasp depends on fast sensory feedback and rapid response time of the gripper. This approach is indeed feasible. However, in future work we will examine alternative approaches. One may include controlling the normal force to slowly decelerate the object against gravity to the desired angle. Moreover, estimation of the objects state could decrease the sensory dependency and inaccuracies in the objects dynamic properties.

Acknowledgements

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