Design and Stabilization of a One Legged Hopping Robot

B.Tech. Project

of

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Certificate

This is to certify that this report of **Pratik Chaudhari** on the topic, **Design and Stabilization of a One Legged Hopping Robot** towards the fulfillment of the requirements of **B.Tech. Project AE 497** is approved by me for submission. It represents the work carried out by the student under my guidance.

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Acknowledgment

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Contents

Abstract

The abstract goes here.
Keywords:
parameter estimation, lyapunov stability of adaptive laws, adaptive control of MAV, fuzzy adaptive control, dynamically focussed learning, magnetic levitation

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Chapter 1

Introduction

This is a test.

Chapter 2

Mechanical Design

As pointed out in the previous chapter, the major task of this project was to devise an efficient mechanical design. Two different designs both based on extension springs were looked into. This chapter describes them and the motivation behind choosing the final design to be fabricated.

2.1 Design 1

Write general description of design 1 here.

2.1.1 Energy pumping

Figure 2.1: Winding motor with pulley on the leg

Fig. 2.1 shows the pulley mechanism for storing energy in the large central spring. The winding motor is placed upon the platform which can be called as the larger mass M of the two mass system. A winch connects the motor to the same platform passing over the pulley on the lower leg. Thus, as the motor rotates, it pulls the platform (and itself) downwards while extending the spring above it. A few points to note about the energy pumping design are,

1. The motor has to move a distance twice that of the extension of the spring. This is especially important when we look at the timescales over which we have to extend the spring, these are around 200-300 msecs. A larger distance in smaller time results in a large ω for the motor which translates to a smaller available torque. This neccesitates a larger motor which can provide this torque.

2. The large mass of the platform (M) is helping in the extension of the spring and hence the torque required for the winding motor reduces.

3. It has to be ensured that the winding winch does not slip over the pulley when the platform is suddenly released from the constraint. At the same time, the winch must be free enough so as not to hinder the movement of the platform after the release.

2.1.2 Constraint

Figure 2.2: Constraint for the pulley

Fig. 2.2 shows the constraint mechanism for the pulley. It consists of a hatch connected to the lower leg with a torsional spring. The toothed part of the pulley is free to move in the clockwise direction (thus compressing the torsional spring every time). The lower part of the leg is cylindrical with a top flange which matches the top face of the cylindrical bushing shown inside the main leg. Thus the lower leg can move only up. The protruding portion of the main leg prevents the hatch from moving in the clockwise direction, thus constraining the pulley from rolling back in the anti-clockwise direction. Salient points of this part are,

1. The diameter of the lower leg is expected to be around 2-3 cms and it is difficult to fabricate the hatch on such a small surface.

2.1.3 Using the impact for energy release

This design is unique because it utilizes the impact force ($m\, v_{touch-down}$) to release the stored energy in the main spring. Visualize the lower leg impacting on the ground. This results in the hatch (which is holding the pulley from moving back) impacting against the protrusion of the main leg. Since the impact force is easily larger than the torsional spring force, the hatch closes and the lower leg goes inside the main leg thus enabling free rotation of the pulley. There is a compression spring inside the main leg connected to the lower leg which gets compressed while this happens. It is responsible for pushing the lower leg back outside after $t_{liftoff}$.

2.2 Design 2

2.2.1 Energy pumping

The leg consists of a rack on one of its sides. A single dual shaft motor in a sleever is used to drive the pinion on this rack as well as pull the paul to free the ratchet. This motor consists of a string attached to a friction pulley on the shaft. A friction pulley is a device whose coupling is dependent upon the speed of the relative motion between the two surfaces. Thus, the motor can pull the paul only beyond a certain ω. Below this speed, the paul spring is enough to engage it with the ratchet.

2.2.2 Constraint

The platform and the ratchet are rigidly connected to a band drive which rolls along the length of the leg. This ensures that contact of the roller inside the band drive and the leg is maintained at all times. Since the ratchet is rigidly connected to the platform, both can only move together i.e. only when the paul is pulled by the drive motor.

2.2.3 Energy release

This design uses an electromechanical system to release energy. After sensing the impact through a touch switch located below the leg, we can use a voice coil actuator to slack the string attached to the paul. This brings in the pull back spring attached to the sleeve into the picture and it prompty pulls the sleeve away from the rack. **Not sure about this part.**

2.3 Modifications

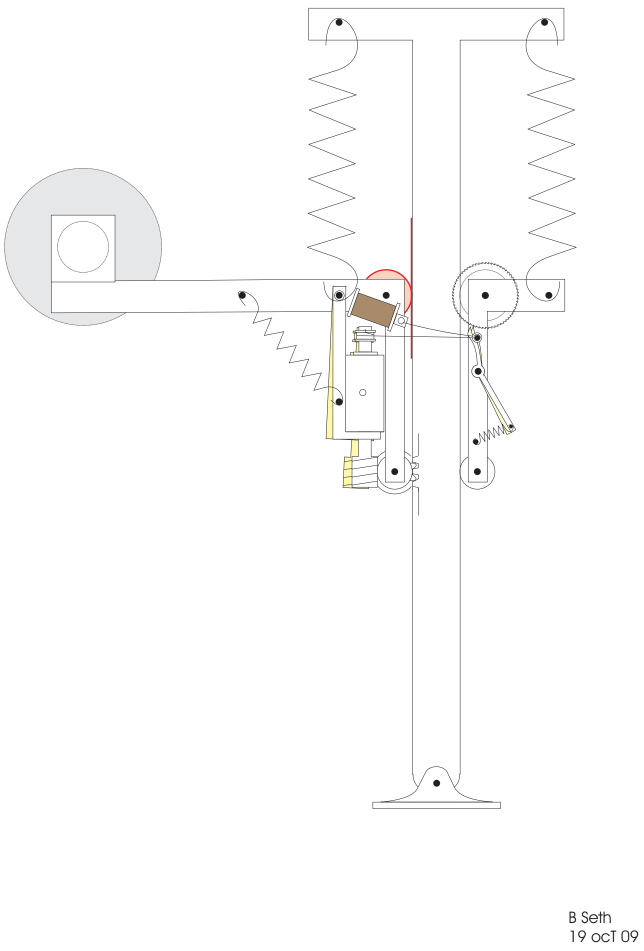

Figure 2.3: Rack and pinion on the leg with the drive motor

Chapter 3

Sizing of Hardware

This chapter details the sizing of the various components of the design chosen in Chapter 2. The major parts of this process are,

1. Masses of the platform and the leg
2. Dimensions of the reaction wheel based on the above masses
3. Choice of winding and reaction wheel motors

3.1 2 mass problem

Figure 3.1: 2 mass problem

The basic idea behind a hopper is like that of the 2 masses connected by a spring problem. If the system shown in Fig. 3.1 is allowed to fall from a height, the heavier mass pulls the smaller mass with it back into the air after impact. Every cycle is accompanied by a loss in energy due to the inelastic impact of the smaller mass with the ground. If we pump this energy back into the system using an external agent in every cycle, we can ensure sustained hopping at the chosen height. The 2 mass problem can thus be taken as a basis to compute the range of values of masses for acceptable performance. The following assumptions have been used in the simulation that follows,

1. Dropping height (H) : 0.6 m
2. Spring constant (k) : 300 N/m
3. Spring relaxed length (l_0) : 0.3 m
4. Trapezoidal profile for ω of the winding motor (constant α at the start and end)
5. Faulhabeur 2342CR024 motor with a 3.71 reduction gear-box for comparison of torques
6. Neglect energy loss due to friction

It is seen from Fig. 3.1 that if h_i are progressive heights, we have the relation,

$$h_n = \frac{Mh_{n-1} + ml_0}{M + m} \tag{3.1}$$

$$E_{loss} = \frac{Mg\,(H - l_0)}{1 + M/m} \tag{3.2}$$

Figure 3.2: Hopping height for different M/m

From Fig. 3.2, it is seen that larger the ratio M/m, i.e. smaller the leg mass, less is the loss in energy resulting in more number of hops. This is also seen for a increasing M. We would however, like the M to be within limit too as we will also need to pump in extra energy into the system if the desired hopping height is more than the starting height.

How to solve the torque for a rack and pinion?

3.2 Impact analysis

The desired hopping height dictates a hopping frequency. Smaller hopping height results in large number of impacts per time and consequently in larger energy loss per unit time. However, beyond this consideration, since the hopper is a spring mass system, it possesses a natural frequency of its own. If the hopping frequency is near to this natural frequency, a large amount of energy is taken away by impact forces in every cycle. We intend to arrive at a range of values for the masses to ensure a large difference between the hopping frequency (ω_{hop}) and the natural frequency (ω_{nat}). The details of this analysis are as follows,

- Conserve energy at H and the moment of maximum extension of the spring after $t_{touchdown}$ to get the minimum height of the fully extended platform above the leg. This comes out to be 8 cms for m = 0.4 kg. This value also reduces with increasing m. I assumed no pre-extension of the spring while calculating this. The final value will be less then 8 cms if we take it into account. Thus we say that the leg should protrude about 12 cms beyond the maximum extension of the platform which is obtained from Fig. 3.2.
- If x_2 is the height of C.G. just before touchdown, we can calculate the time taken for it to fall from a height H to x_2 as t_1.
- M undergos simple harmonic motion from time t_1 till liftoff, and this time of motion is t_2
- M transfers its momentum at $t_1 + t_2$ to m resulting in a velocity v_{cg,t_2} for the C.G. To ensure that M has largest velocity while transfering momentum to m, we need to put a mechanical stopper at the natural length of the spring.
- The resultant velocity is just enough for the C.G. to reach a height H in time t_3.
- Total hopping time T = $t_1 + t_2 + t_3$, with $\omega_{hop} = \frac{2\pi}{T}$.
- $\omega_{nat} = \sqrt{\frac{k\ (1+m/M)}{m}}$

Figure 3.3: Frequency variation with hopping height for M/m = 5

Fig. 3.3 shows that ω_{hop} and ω_{nat} are seperated by large gap for the usable range of values of hopping height. A similar analysis for variation of M also reveals that the two frequencies are seperated by a large gap for all usuable values. Fig. 3.4 succintly depicts all the above analysis. As the leg mass

Figure 3.4: Frequency variation with m

increases, the hopping frequency goes closer to the natural frequency i.e. more impact per unit time.

To compound matters, more and more energy is lost per impact as per Eqn. 3.2. So the conclusion from impact analysis is that the leg mass should be as low as possible. It is also seen from Fig. 3.4 that m = 0.4 – 0.6 kg is a good solution as well as an achievable one.

3.3 Reaction wheel

For achieving a running gait with the hopper, it has to be started with the exact initial pitch and horizantal velocity. For any other initial condition, the hopper is pitch unstable and will not be able to continue the running gait. As mentioned in (cite shanmukh...), an offset mass acts as a passive stabilization to the pitch attitude of the hopper. To get rid of this need for exact initial condition which is quite impracticable, we design a reaction wheel on the hopper. This will result in torque coupling on the pitch axis and thus provide an active control over the pitch of the robot. The coupling equation can be written as,

$$J_{wheel}\,\omega_{wheel} = -(J_{wheel} + J_{body})\,\omega_{body} \tag{3.3}$$

The following considerations are made for this analysis,

Figure 3.5: Stabilizing impact torque due to SLOM

- The reaction wheel is taken as a ring with mass concentrated at the rim.
- Let θ_{impact} be the impact pitch attitude and $\theta_{liftoff}$ be the lift-off attitude. Pitch is measured with respect to the vertical direction. An upright hopper means a pitch of zero.
- From Fig. 3.5, the stabilizing impact torque is given by $\tau_{impact} = m\,v_{impact}\,(h_M sin\,\theta + d_{cg} cos\,\theta)$. This is positive torque and generates a pitch up. Thus we have a $\omega_{liftoff} = \tau_{impact}\,/J_{body}$
- The angle rotated due to horizantal velocity in the stance phase is $\Delta\,\theta = -v_h\,/h_{cg}\,\Delta\,t$. This means $\theta_{liftoff} = \theta_{impact} + \Delta\,\theta$.
- The lift-off pitch needs to be corrected to θ_{impact} while the hopper is in the air. $\omega_{liftoff}$ might not be enough to correct this pitch and so we need an additional reaction wheel.
- We assume a trapezoidal profile for ω_{wheel} with length of the plateau taken as $0.3\,T_{air}$. The acceleration phase is $0.2\,T_{air}$ on either side. This means that we finish the reorientation task within 7/10s of the total time the hopper remains in the air ($T_{air} = t_1 + t_3$ from Section 3.2).

Figure 3.6: Torque requirements vs wheel radius

Figure 3.7: Torque requirements vs C.G. offset

3.4 Choosing the motors

Chapter 4

Embedded System

This chapter details the development of the embedded system necessary for controlling and actuating the hopper. It consists of two major parts yet,

1. Micro-controller and RF interface

2. Inertial Measurement Unit (IMU)

4.1 Micro-controller

This microcontroller chosen for this system is a Microchip dsPIC33F64MC804. It can run at 40 MIPS with an onboard flash memory of 64 KB along with a 16 KB SRAM. There are a host of integrated peripherals like Serial Peripheral Interface (SPI), UART, Analog to Digital convertor (ADC), Digital to Analog Convertor (DAC) and Timers to generate Pulse Width Modulation (PWM) that can be used. Other major features provided with it are the Direct Memory Access controller (DMA) which can transfer memory from one peripheral to other without CPU intervention and the high multiplexing of its IO pins. The latter enables almost all IO pins to be assigned to any of the above mentioned peripherals (except analog pins) and greatly simplifies design. Pickit 2 is a programmer cum debugger that had been ordered for programming the micro-controller.

XBee modules using the Zigbee protocol are used to form a wireless link with the embedded system on the hopper. The range of these devices is quite sufficient for indoor uses (about 100 m). The interface on the microcontroller side is through UART and a custom made FT232 module will be used to interface it with the base station to gather telemetry. A python module to grab and plot this telemetry from the virtual serial port of FT232 is in development.

The current development board contains one motor driver and its adjoining encoder port. The final module will contain two motor drivers and encoder arrangements for the pinion and the reaction wheel motors.

4.2 Inertial Measurement Unit