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Development of a reaction drive for a propulsion mechanism

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***Abstract*—A micro robot that can be swallowed with sensors to inspect the intestine without the need to cut open a patient must have a propulsion mechanism to direct it to the areas of interest. The use of a propulsion mechanism external to the pill could endanger the patient, what is proposed here is a method of propelling a micro (capsule) robot with an internal mechanism based on the inertia of a swinging mass. The dynamics and control issues of a pendulum-driven cart-pole system are similar to those of a capsule robot. Therefore, this paper reports an experimental study of a pendulum-driven cart-pole system. The experimental results demonstrate the proposed system.**

***Index Terms*—micro-robot, propulsion, medical inspection**

I. INTRODUCTION

MEDICAL uses for robotics is on the increase. This is due to the population living longer and birth rates stabilizing-hence there are fewer people to look after the elderly and medical assistance needs to be optimized. Diseases of the gut which requires gastrointestinal endoscopy for examination can be improved by the use of a wireless capsule endoscope. The first capsule endoscope [1] was developed and commercialized in 2001 by Given Imaging Inc. of Israel. It is 27mm long and 10mm in diameter and contains an RF module, a camera and LEDs. This has been improved by [2] where the capsule contains a motor allowing a camera to rotate and gather complete data. These capsules move passively through the body, there is no locomotive mechanism to allow active diagnosis. Locomotive mechanisms have been discussed [3,4] and these rely on the heating of shape memory alloy or the effects of a piezo actuator with a self contained power source. Another application has investigated external power being provided in the form of rotating magnetic fields [5]. This paper looks at a particular application of a propulsion system[6] that could be used in a capsule robot, this relies on internal inertia and thus there are no propellers, legs or wheels to snag in the patient's gut. The drive is produced by the opposite reaction of the body to a driven pendulum shown in Figure 1.

This device consists of passive wheels and a motor driven inverted pendulum supporting a mass. Movement of the mass results in motion of the cart as a reaction to this, motion of the pendulum and cart is tracked using optical encoders. This system is used as a testbed to try out the reaction theory allowing the researchers to specify the torque / time of the driving motor and to download and view the movement of the pendulum and the exact motion of the robot over time. This could also find an application in space propulsion, sewerage inspection, etc.

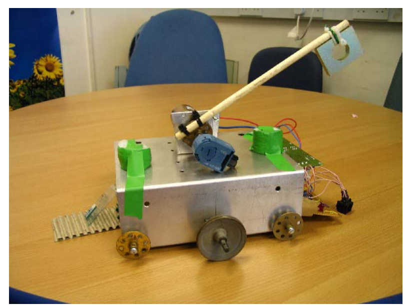

Figure 1. The developed prototype

II. MODELLING OF THE INVERTED PENDULUM

A mass is attached to the shaft of a geared motor via a link at right-angles to the motor shaft. Rotation of the motor will result in the mass orbiting the motor shown in Figure 2. The system consists of a straight-line rail, a cart, a link and a ball. The cart can move left freely but is inhibited from moving right by a ratchet mechanism. The pendulum is hinged on the centre of the top surface of the cart and can rotate around the pivot in the same vertical plane with the rail. M, m_l and m_b are the masses of the cart, link and ball, respectively. L is the length of the link, I is the inertia of the pendulum, b_c and b_l are the coefficients of the friction of the cart and the joint rotation, q_1 is the cart position co-ordinate, q_2 is the pendulum angle from vertical, τ is the torque applied to the joint of the pendulum. A rachet mechanism allows the cart to travel in one direction only.

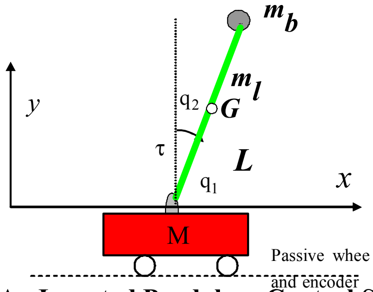

Figure 2 An Inverted Pendulum Control System with a driving torque on the joint

Next, we will derive the dynamic models of the inverted pendulum system by using the Euler-Lagrange method.

The co-ordinate of the link point G and the ball are
$x_G=q_1+0.5L\sin q_2$ and $y_G=0.5L\cos q_2$
$x_b=q_1+L\sin q_2$ and $y_b=L\cos q_2$

The velocities of point G and the ball are
$\dot{x}_G=\dot{q}_1+0.5L\dot{q}_2\cos q_2$ and $\dot{y}_G=-0.5L\dot{q}_2\sin q_2$
$\dot{x}_b=\dot{q}_1+L\dot{q}_2\cos q_2$ and $\dot{y}_b=-L\dot{q}_2\sin q_2$

The kinetic energy of the pendulum system is

$$\begin{aligned}K&=K_c+K_b+K_l\\&=0.5M\dot{q}_1^{\,2}+0.5m_b(\dot{x}_b^2+\dot{y}_b^2)+0.5[I\dot{q}_2^{\,2}+m_l(\dot{x}_G^2+\dot{y}_G^2)]\\&=0.5M\dot{q}_1^{\,2}+0.5m_b(\dot{q}_1^{\,2}+L^2\dot{q}_2^{\,2}+2L\cos q_2\dot{q}_1\dot{q}_2)\\&\quad+0.5[I\dot{q}_2^{\,2}+m_l(\dot{q}_1^{\,2}+0.25L^2\dot{q}_2^{\,2}+L\cos q_2\dot{q}_1\dot{q}_2)]\\&=\frac{1}{2}[\dot{q}_1\quad\dot{q}_2]\begin{bmatrix}M+m_b+m_l&\frac{1}{2}L(2m_b+m_l)\cos q_2\\\frac{1}{2}L(2m_b+m_l)\cos q_2&I+\frac{1}{4}L^2(2m_b+m_l)\end{bmatrix}\begin{bmatrix}\dot{q}_1\\\dot{q}_2\end{bmatrix}\end{aligned}$$

where K_c, K_b, K_l are the kinetic energies of the cart, the ball and the link respectively. The potential energy of the pendulum system is

$$P=P_b+P_l=Lm_bg(\cos q_2-1)+\tfrac{1}{2}Lm_lg(\cos q_2-1)$$

where P_b and P_l are the potential energies of the ball and the link respectively. It is noted that the potential energy is zero when the pendulum is in the upward position. The equations of motion can be obtained using the following Euler-Lagrange formulation

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{q}}\right)-\frac{\partial L}{\partial q}=\tau$$

where the Lagrange function L=K-P, the general co-ordinate $q=[q_1\quad q_2]^T$, the general force $\tau=\Gamma u+\zeta-\frac{dF(\dot{q})}{d\dot{q}}$, $F(\dot{q})$ is the Rayleigh dissipation function, and ζ is the external disturbances vector which will be neglected in this study. For the pendulum system studied, the Rayleigh dissipation function is

$$F(\dot{q})=0.5b_c\dot{q}_1^{\,2}+0.5b_l\dot{q}_2^{\,2}$$

Using the above, we have

$$\frac{\partial L}{\partial\dot{q}}=\begin{bmatrix}M+m_b+m_l&\frac{1}{2}L(2m_b+m_l)\cos q_2\\\frac{1}{2}L(2m_b+m_l)\cos q_2&I+\frac{1}{4}L^2(2m_b+m_l)\end{bmatrix}\begin{bmatrix}\dot{q}_1\\\dot{q}_2\end{bmatrix}$$

$$\frac{\partial L}{\partial q}=\begin{bmatrix}0\\-(m_b+0.5m_l)(\dot{q}_1\dot{q}_2-1)L\sin q_2\end{bmatrix}$$

$$\frac{d}{dt}\left(\frac{\partial L}{\partial\dot{q}}\right)=\begin{bmatrix}M+m_b+m_l&\frac{1}{2}L(2m_b+m_l)\cos q_2\\\frac{1}{2}L(2m_b+m_l)\cos q_2&I+\frac{1}{4}L^2(2m_b+m_l)\end{bmatrix}\begin{bmatrix}\ddot{q}_1\\\ddot{q}_2\end{bmatrix}-\frac{1}{2}L(2m_b+m_l)\sin q_2\begin{bmatrix}\dot{q}_2^{\,2}\\\dot{q}_1\dot{q}_2\end{bmatrix}$$

$$\frac{d}{d\dot{q}}F(\dot{q})=\begin{bmatrix}b_c\dot{q}_1\\b_l\dot{q}_2\end{bmatrix}$$

Putting the above into the Euler-Lagrange equation gives

$$D(q)\ddot{q}+C(q,\dot{q})\dot{q}+A\dot{q}+G(q)=\Gamma u\qquad(5)$$

where

$$D(q)=\begin{bmatrix}M+m_b+m_l&\frac{1}{2}L(2m_b+m_l)\cos q_2\\\frac{1}{2}L(2m_b+m_l)\cos q_2&I+\frac{1}{4}L^2(2m_b+m_l)\end{bmatrix}$$

$$C(q,\dot{q})=\begin{bmatrix}0&-\frac{1}{2}L(2m_b+m_l)\sin q_2\dot{q}_2\\0&0\end{bmatrix}$$

$$G(q)=\frac{\partial P}{\partial q}=\begin{bmatrix}0\\-(m_b+\frac{1}{2}m_l)Lg\sin q_2\end{bmatrix}$$

$$A=\begin{bmatrix}b_c&0\\0&b_l\end{bmatrix},\ \Gamma=\begin{bmatrix}0\\1\end{bmatrix}$$

It can easily be seen that D(q) is symmetric and positive. We also have

$$\dot{D}(q)-2C(q,\dot{q})=\frac{1}{2}L(2m_b+m_l)\sin q_2\dot{q}_2\begin{bmatrix}0&1\\-1&0\end{bmatrix}\qquad(6)$$

which is a skew-symmetric matrix. The total energy of the pendulum system is

$$E=K+P=\tfrac{1}{2}\dot{q}^TD(q)\dot{q}+(m_b+\tfrac{1}{2}m_l)Lg(\cos q_2-1)\ (7)$$

Without losing the generality, we neglect the disturbance effect for a moment. Taking the derivative of (7) and using (6) gives

$$\begin{aligned}\dot{E}&=\dot{q}^TD(q)\ddot{q}+\frac{1}{2}\dot{q}^T\dot{D}(q)\dot{q}+\dot{q}^TG(q)\\&=\dot{q}^T[-C(q,\dot{q})\dot{q}-G(q)+\tau]+\frac{1}{2}\dot{q}^T\dot{D}(q)\dot{q}+\dot{q}^TG(q)\ (8)\\&=\dot{q}^T\tau=\dot{q}_1u-b_c\dot{q}_1^2-b_l\dot{q}_2^2\end{aligned}$$

From (8) we can see that the friction helps stabilising the system. Therefore in the stability analysis, we can safely neglect the friction terms. Integrating both sides of (5) gives

$$\int_0^t\dot{q}_1u=E(t)-E(0)\geq-Lg(2m_b+m_l)-E(0)\ \ (9)$$

This implies that the system having u as input and $\dot{q}_1$ as output is passive.

The input to the motor mechanism will be a torque that would be pre-calculated to give the desired position, velocity and acceleration profile of the pendulum. The torque values are defined with respect to time and pre-loaded into of the controlling program of the micro-controller. These torque values are scaled to represent percent power where a positive value represents clockwise motion and negative represents anti-clockwise motion.

III. Implementation and Results

The parameters of the cart in the implementation are as follows: Mass of cart=0.9kg, ball mass=0.3kg, length of pendulum=0.47m, coefficient of friction=0.5.

The motor is driven through a 30:1 planetary gearbox resulting in a maximum torque (τ_{max}) of 0.391 Nm and speed of 20.94 rad.s^{-1}.

The maximum torque required to produce an acceleration in the worst case scenario when the mass is in a horizontal position is related to the mass by the equation:

$$\tau_{max} = ml(\ddot{q}_2 + g)$$

Where T is the torque in N.m^{-1}, m is the mass in kg, $\ddot{q}_2$ is the acceleration in m.s^{-1} and g is the gravitational constant.

Hence, the maximum acceleration the motor can give the mass is:

$$\ddot{q}_2 = \frac{\tau_{max}}{ml} - g$$

The motor driver is a dedicated MD22 device available from [7], it is capable of driving a motor at 5A and is connected to the I^2C bus of a microcontroller to generate pulse width modulated voltage to the motor.

A 500ppr quadrature encoder configured to count on both rising and falling A and B channel edges, thus giving an effective 2000ppr is attached to the motor shaft and position data is sampled with an angular resolution of 0.18° per pulse in order to output the position the motor has moved.

The pendulum is fixed at a starting angle of 45° and travels in an anti-clockwise motion. The motor is given varying power depending on time and this can be varied in the software. For our experiment, the motor was driven clockwise at 56% power for 50ms (the acceleration phase of the pendulum driving the mass), the power was then reversed at a value of 60% in the opposite direction for a further 50ms (braking phase of the mass), and then the pendulum reversed at 29% power for a further 100ms (returning the pendulum to start position). The power / time graph can be seen in figure 3. The whole procedure is repeated three times for analysis of the cart position (total time is 600ms).

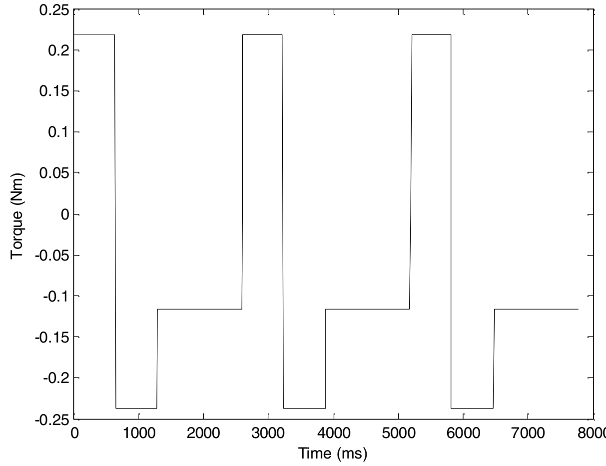

Figure 3. The power/time for the motor driving the motor

The encoder positions of the pendulum and the cart wheels are sent to a PC using the RS232 serial line at a baud rate of 57600. This is captured using the Hyperterminal program and imported into the Excel program for analysis and scaling. The results in figure 4 show the pendulum angle/time, and figure 5 shows the cart position/time. Figures 6 and 7 show the joint velocity and acceleration, respectively. It can be seen that the joint velocity and acceleration are very noisy. These have to be taken into consideration when we design the control algorithm in our next step of research.

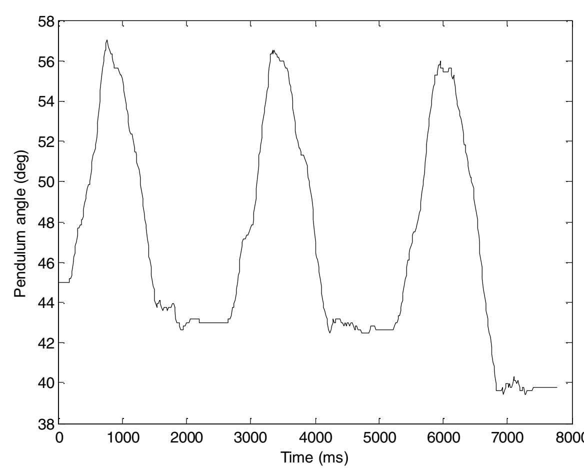

Figure 4. The joint angle, q_2

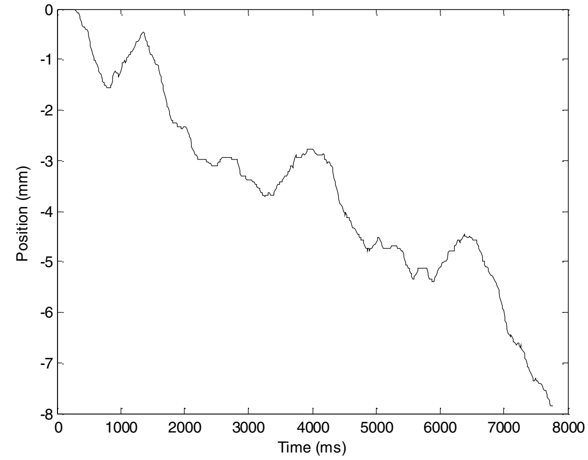

Figure 5. The cart position, q1

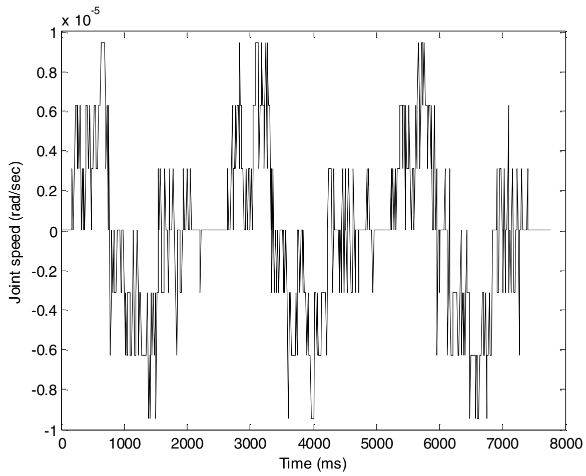

Figure 6. The joint speed $\dot{q}_2$

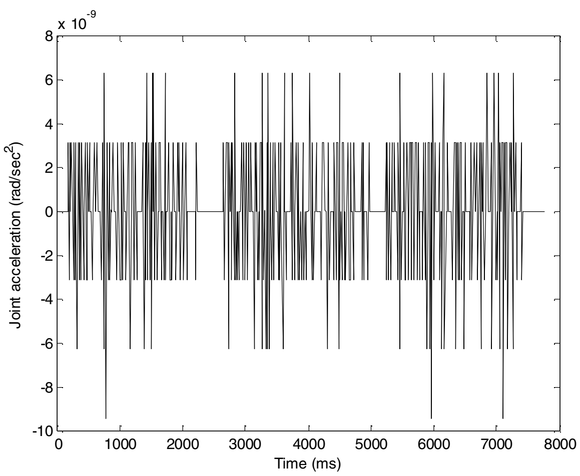

Figure 7. The joint acceleration $\ddot{q}_2$

IV. LATERAL MOTION

The cart has independent passive wheels on both sides allowing it to rotate as well as translate. Encoders outputting an effective 2000ppr are attached to the wheels having diameter 52mm giving a resolution of 0.08168mm per pulse. The cart's rotational motion is restricted, and a set of guidance rails are placed for the wheels to settle into, much like a rail track, the full effect of lateral only motion is therefore examined.

Static friction is introduced into the cart by means of a simple ratchet mechanism. A flexible 'tail' trails the cart and contacts a corrugated mechanism on the ground. The recommended surface for this system is a hard rubber mat and this ensures the encoding wheels do not slip.

V. COMPUTER CONTROL METHODS

The controller is a PIC16F877[8] , this allows up to 8K of program memory, 368 bytes of data memory, and 256 bytes of EEPROM. The raw A-B encoder data is read directly into the PIC inputs. The results of the encoders is uploaded to a PC using the serial cable for later analysis.

VI. CONCLUSIONS

It is possible to implement a test bed for a novel propulsion technique using a PIC microcontroller, a motor driver, motor and three encoders. The data representing the torque of the motor for each sample time can be downloaded from a PC and altered for each experiment. The data can also be uploaded from the PIC for later analysis. This will take the form of reconstructing the cart's position and rotation for each of the sample periods as well as the actual position of the pendulum throughout. The current experimental system is controlled using an open-loop strategy. This is mainly to prove the concept developed and simulated by another team in the research group. Our next move is to make a comparison with the results from our simulation study. Our long term goal is to develop a propulsion mechanism for capsule robots.

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