Control of a propulsion mechanism over a wireless network

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Abstract: This paper investigates the implementation of a pendulum-driven cart-pole system through wireless networks. The system is underactuated since the only control input is the motor which drives the pendulum movement while the cart has free movement wheels. An onboard client PC controls the torque to the motor, whilst a host PC monitors progress and controls the demand to the motor. The two PCs have been connected via a proprietary wireless network to allow the controller to be remote from the robot. The client PC interprets commands sent via the network from the host PC to control the torque of the pendulum device. The client PC also relays the pendulum position which the host PC uses as feedback to specify the torque to send.

1. INTRODUCTION

The ethernet is a flexible communication medium where the resulting end points of communication are screened from the application. The wireless (WiFi) internet connection was utilised in this experiment to test its effectiveness on a closed loop time critical system. The experiment consists of a controlling host computer that is to update the torque of the motor driving an inverted pendulum of the system connected to a remote (client) computer. The client reports the pendulum angle using an encoder attached to this motor and returns this data to the controlling computer thus closing the loop. The inverted pendulum system is propelled laterally by the effect of the reaction to the pendulum swing (Hongyi et.al 2005,2006). Since the high-level control is performed wirelessly, this results in a simplified control system on the robot, and the complex control being performed remotely.

2. THE CART HARDWARE

A cart having four passive wheels and a driven inverted pendulum has been built in previous experiments (Wane et.al 2007a). This consists of a geared motor with an attached encoder, that drives a mass attached to a rod (driven inverted pendulum). It also has four passive wheels for stability and a wheel attached to an encoder to monitor the distance the cart travels.

The base of an inverted pendulum is attached to the shaft of a DC motor. The body of the motor is fixed to the centre of the base of the cart. An incremental rotary encoder shaft is attached to the motor shaft to provide feedback of the pendulum angle. The encoder body is also attached to the cart.

A diagram of the hardware appears in figure 1.

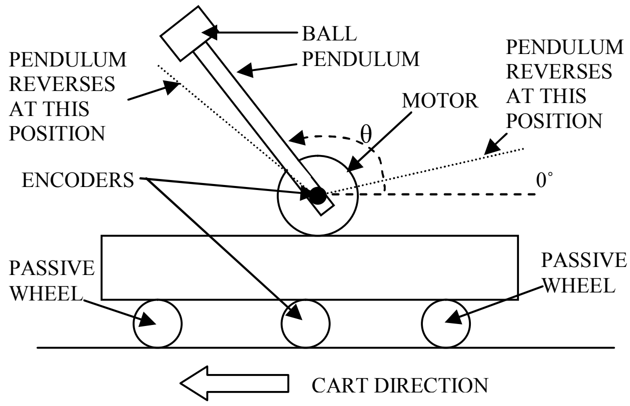

Fig 1 Schematic of the driven inverted pendulum

The parameters of the cart in the implementation are as follows: Mass of cart=923g, ball mass=119g, length of pendulum=0.165m. The pendulum length was chosen through experimentation between the motor comfortably accelerating, and the mass having an optimum influence on the cart motion.

The motor is driven through a 30:1 planetary gearbox resulting in a maximum torque (T_{max}) of 0.391 Nm and speed of 20.94 rad.s^{-1}. with an input of 12V and drawing a current of 3.1A. The relationship between torque and velocity is assumed to be linear as shown in figure 2.

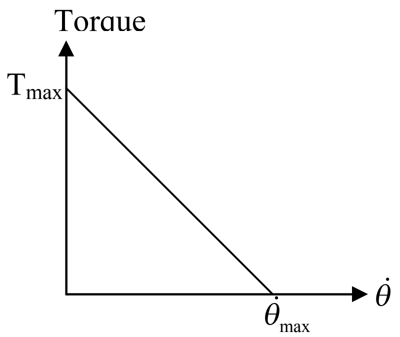

Fig 2 Torque vs angle graph

The maximum acceleration/deceleration of the mass occurs when the normal to the plane of motion is horizontal, in order to produce a reaction in the opposite direction.

This is related to the mass by the equation:

$$T_{max} = ml(\ddot{\theta} + g)$$

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

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

$$\ddot{\theta} = \frac{T_{max}}{ml} - 0$$

This results in a maximum acceleration of 17.83 $m.s^{-1}$.

Static and dynamic friction tests were conducted on the cart system placed on the rubber matting by using a spring balance. The cart was pulled by the spring balance until it just started to move. Friction can be calculated using:

$$\mu = \frac{F_{SPRING}}{F_{NORMAL}}$$

The force required to move the cart from a stationary position was found to be 0.14N, and the force required to keep it at a constant velocity was 0.06N. Knowing the normal force of the cart to be 10.22N (from its mass), the static and dynamic friction coefficients were found to be μ=0.014 and μ=0.0059 respectively. The cart parameters are summarised in table 1.

Table 1. Cart Parameters

Mass of cart and motor	923g
Mass of ball	119g
Length of pendulum	0.165m
Motor gearbox ratio	30:1
Maximum motor torque	0.391
Maximum motor speed	20.94
Static friction of cart	0.014
Dynamic friction of cart	0.0059
Encoder types	500ppr, A & B channel

2.1 Motor Driver

The minimum torque required to lift the pendulum from 0˚ is calculated from:

$$T_{min} = F \times l$$

where T_{min} is the torque delivered by the motor, F is the force exerted by the mass of the ball due to gravity, and l is the pendulum length. This minimum torque is calculated to be 0.193 Nm. Simulation from (Wane et.al 2007b) has shown that sufficient progress can be made with a maximum torque of 0.35 Nm.

What was required was an accurate method of controlling the motor torque. This could not be accurately achieved by controlling the voltage to the motor using PWM or otherwise due to the back EMF or voltage generated by the motor which is proportional to its velocity.

Motor torque (T_m)is proportional to armature current (I_a) regardless of the shaft velocity:

$$I_a = \frac{T_m}{K_t} \quad \text{...(1)}$$

where T_m is the torque developed by the motor and K_t is the motor torque constant.

A constant current driver circuit was developed and improved from the Howland Current Source 0, the input is a voltage in the range of 0-3.4V and the output is a current in the range of 0-1.26A. This driver is able to drive a motor bi-directionally. A negative voltage drives the current to a negative value and turns the motor the opposite direction.

The operation of the circuit is as follows (figure 3):

Operational amplifier U2 acts as a voltage buffer for voltage V_2. Operational amplifier U1 adds the voltages V_{IN} and V_2 and outputs this to V_1:

$$V_1 = V_{IN} + V_2 \quad \text{...(2)}$$

The resistor R_{REF} determines the current, since:

$$R_{REF} = \frac{V_1 - V_2}{I_a} = \frac{V_{IN}}{I_a} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3)$$

and combining (3) with (1) gives the relationship:

$$V_{IN} = \frac{T_m R_{REF}}{K_T} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots....(4)$$

The relationship of voltage to current is linear.

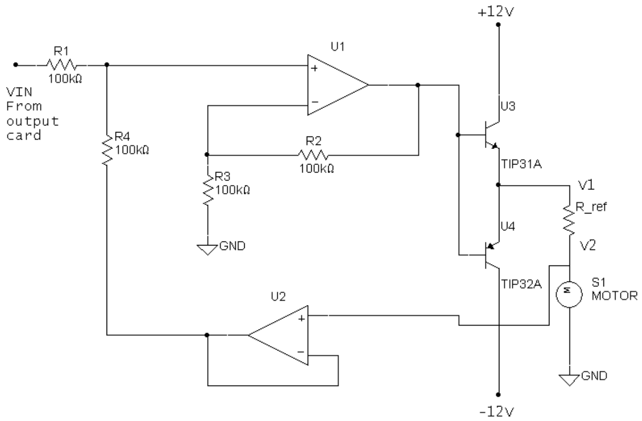

Fig 3 The constant current driver circuit

The value R-ref is 0.76Ω.

The motor's stationary torque was measured for the input voltages in the range of 0-3.24V by having the motor move a bar of length 0.3M resting on a digital scale having an resolution of 1 gram. The results were a linear relationship between input voltage and the developed torque in the required range of 0.193 – 0.35 N.m. as shown in figure 4 with the exception of the initial torque. This is due to the friction of the gearbox and the graph shows this to be 0.063N.m.

Using the graph, the relationship between the input voltage and the torque is found to be:

$$\frac{R_{REF}}{K_T} = 9.26, \text{ or:}$$

$$V_{IN} = 9.26 \times T_m$$

Since R_{REF} is fixed in the circuit at a value of 0.76Ω, K_T has a value of 0.081. From (1), the maximum torque we can expect from a 5A power supply is therefore 0.405 N.m, this is within the specified range.

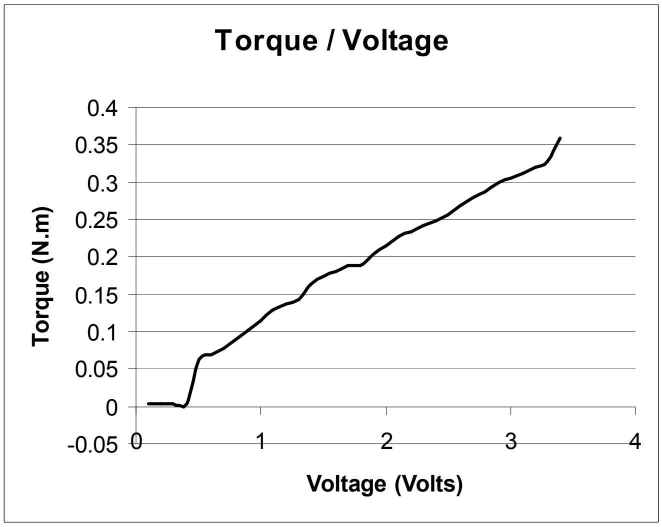

Fig 4 Voltage / torque ratio

2.2 Interface

The motor driver was connected to the output of the analogue output channel of the DAQ card.

A motor driving a pendulum with an attached mass is attached to the cart. Interfacing with two encoders and the driving motor is accomplished by using an I/O card, a digital acquisition (DAQ) National Instruments 6221 PCI M-series 16 bit, 250 KS/s card (National Instruments 2007b) having two analogue output channels and two encoder counter channels.

The encoders are 500ppr quadrature type, having both A and B channels to distinguish direction on the system, one monitors the pendulum angle and the other monitors the cart position. The encoders are read directly via the counters on the DAQ card.

An encoder is attached directly to the motor shaft, and position data is sampled with an angular resolution of 0.72° per pulse in order to output the position the motor has moved. The encoder sampling property was set to count both the rising and falling edges of both A and B channel pulses for greater accuracy as the encoder rotates at low speed.

and the motor is connected to the analogue output channel via a voltage to current amplifier.

The encoder is read using Labview, the elements of the code to accomplish this are shown in figure 5. This consists of two blocks representing functions. First, the angular encoder number 0 (ctr0) is instantiated to interface to device 1 (Dev1), with no z-index, 500 pulses per revolution, encoding type X4 (counts both edges of A and B pulses), and zero starting angle.

The encoder is subsequently read using the second function block. This reads the raw (tick) data from the encoder to be processed further in the program.

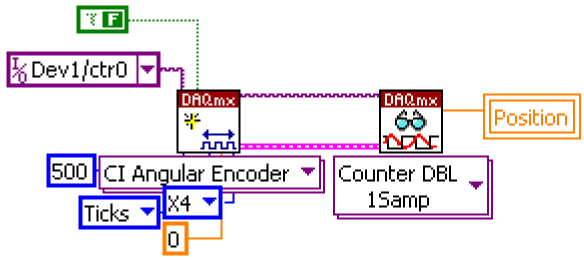

Fig 5 Software reading the encoder interface

2.3. Monitoring Lateral Progress

The cart has four independent passive wheels on both sides giving it stability and inhibiting rotation. Encoders outputting an effective 2000ppr are attached to a fifth passive wheel having diameter 52mm giving a resolution of 0.08168mm per pulse.

This is interfaced to the DAQ card via a second counter input and a program written in 'Labview' graphs the progress in mm against time. This data is also saved to disk for later analysis in the form of comma separated variables representing: time, pendulum angle and cart displacement (figure 6).

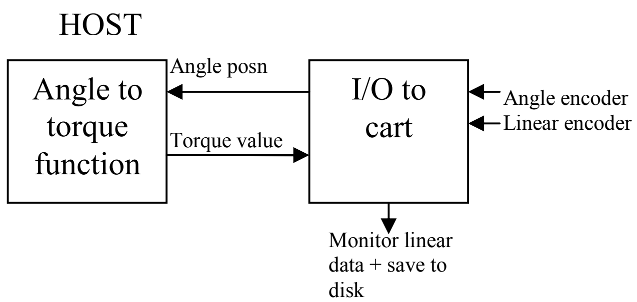

Fig 6 The client - host setup

3. THE COMMUNICATION PROTOCOL

The cart hardware was connected to a remote PC .This was connected to the constant torque motor driver in turn connected to a motor driving the pendulum via a NI 6221 DAQ card. The motor shaft was connected to an encoder which was fed back through the DAQ card to the remote PC to monitor position.

The control consisted of reading the pendulum angle and computing the desired torque. For the controller, a separate PC was used and connected remotely. The remote PC transmitted the position data back to the controlling PC where the torque values were recalculated and transmitted as feedback to the remote PC in order to control the torque.

The controlling computer was separated from the host computer with wireless communication set up between them at a distance of 2m.

USB wireless network adapters supplied by Belkin (type 'Wireless G', 54Mbps) were added to each machine. A peer-peer private 802.11g network was created and activated using the Microsoft wireless connection management utility 'Wireless Zero Configuration'. The remote computer was set as a TCP listener on port 6342 whilst the controller was the host that initiated communication with the remote by opening communication on the same port with its IP address.

TCP (Transmission Control Protocol) sends data as a frame, this frame consists of 7 preamble bytes, the 6 byte recipient address, 6 byte source address, 2 bytes indicating the length of data, the data itself followed by the frame check sequence bytes. TCP is a connection orientated system where the recipient computer sends an acknowledgement for each byte of information sent. This results in a relatively slow but accurate transmission medium. The alternative is UDP (User Datagram Protocol) where no acknowledgement is sent and is ideal for fast streaming data e.g. video.

A programming language had to be chosen that would allow for interfacing motors and encoders via a suitable interface card, and would be robust and allow a quick solution to implementing the TCP/IP protocol. The protocol TCP/IP was used as this does not allow for dropped packets of data but will retransmit any lost data. The programming language 'Labview' allows ease of use in TCP/IP communication. It is a graphical language and functions are connected with virtual wires. The TCP/IP protocol transfers its data as a series of bytes in a string of characters. Figure 7 shows two functions that are used to instantiate a communication with the client computer at ip address 254.169.11.2 on port 6342. The string *Data* is written to this port and sent to the client.

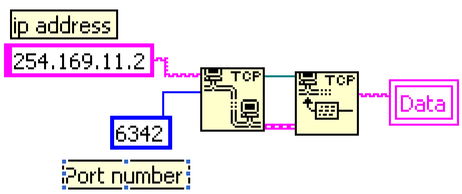

Fig 7 TCP Host program section

The client PC was running a Labview 0 program under Windows, previous research had used a real time system 0 for a faster sample rate however, wireless Ethernet connection is not supported by the real time system and could not be used. This ran a program that sent the pendulum angle to the host at a rate of 10ms. The host processed the angle data and calculated the desired torque value from a user defined function. The torque data was sent from the host to the client to be sent to the torque control card. The client receiving section is shown in figure 8.

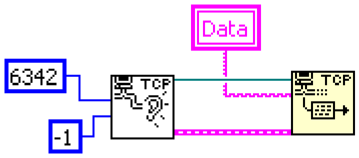

Fig 8 TCP Client program section

4. 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 9. The system consists of a cart, a link and a ball. The cart can move laterally freely in the direction of x. The pendulum is hinged on the centre of the top surface of the cart and can rotate around the pivot. 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.

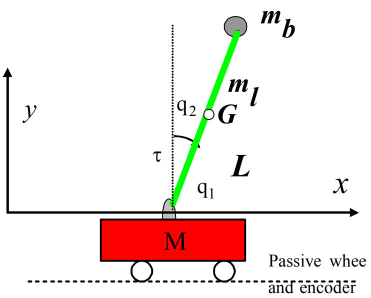

Fig 9 An Inverted Pendulum Control System with a driving torque on the joint

Next, we will derive the dynamic models (Hongyi et.al 2005) 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

$$\dot{x}_G = \dot{q}_1 + 0.5L\dot{q}_2 \cos q_2 \text{ and } \dot{y}_G = -0.5L\dot{q}_2 \sin q_2$$

$$\dot{x}_b = \dot{q}_1 + L\dot{q}_2 \cos q_2 \text{ and } \dot{y}_b = -L\dot{q}_2 \sin q_2$$

The kinetic energy of the pendulum system is

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

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

$$P = P_b + P_l = Lm_b g(\cos q_2 - 1) + \tfrac{1}{2}Lm_l g(\cos q_2 - 1)$$

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

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

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

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

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

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

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

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

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

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

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

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

$$\int_0^t \dot{q}_1 u = E(t)-E(0)\geq -Lg(2m_b+m_l)-E(0) \quad (9)$$

This implies that the system having u as input and $\dot{q}_1$ as output is passive. By controlling the torque to the pendulum, the cart can be controlled laterally.

5. THE CONTROLLER

The controller was able to update the torque in the range of -0.35 to 0.35 N.m to the motor at a rate of 10ms and to control the motor to run in both directions. The chosen controller was a PC running the National Instrument's Labview Operating System 8.0.

A secondary PC is configured as a host terminal and is connected to the remote PC via wireless Ethernet. This secondary computer acts as the visual interface through which the torque profiles can be modified and sent to the remote PC.

In order to drive the cart, a torque is applied to the motor and, the reaction of the moving mass causes the cart to move. By carefully controlling the torque to the motor, this reaction force can be altered to be higher or lower than the static friction of the cart with the ground and the cart can be made to move in one direction only.

5.1 The quantised torque method

The torque sent to the pendulum motor is controlled at the host and is related to the pendulum angle (figure 10).

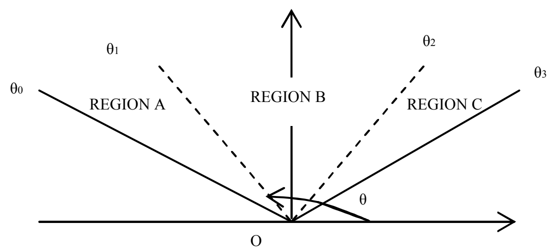

Fig 10 Quantised torque values from pendulum angles

The new torque data (10) is applied in a computer program to output the torques for the angles.

$$\tau=\begin{cases} 0.35 & \theta(k)\in[180^\circ,110^\circ] \\ 0.2 & \theta(k)\in([110^\circ,40^\circ],\theta(k)-\theta(k-1)<0) \\ -0.2 & \theta(k)\in([40^\circ,0^\circ],\theta(k)-\theta(k-1)<0) \\ -0.2 & \theta(k)\in([0^\circ,90^\circ],\theta(k)-\theta(k-1)\geq 0) \\ -0.1 & \theta(k)\in([90^\circ,120^\circ],\theta(k)-\theta(k-1)\geq 0) \end{cases} \quad (10)$$

This torque profile was used in order to pose a direct comparison with previous work (Wane et.al 2007a).

5.2 Continuous torque profile

An improvement on previous work was the ability to accurately control the torque / angle relationship with a 10ms sample rate. This was implemented by having the pendulum gradually increase the torque from its horizontal position until just past upright, at this point the torque would be at maximum. The torque is reversed at a maximum value, decreasing linearly as the pendulum returns towards its horizontal position. Thus the change of acceleration is at its maximum when vertical, and minimum when horizontal as in figure 11.

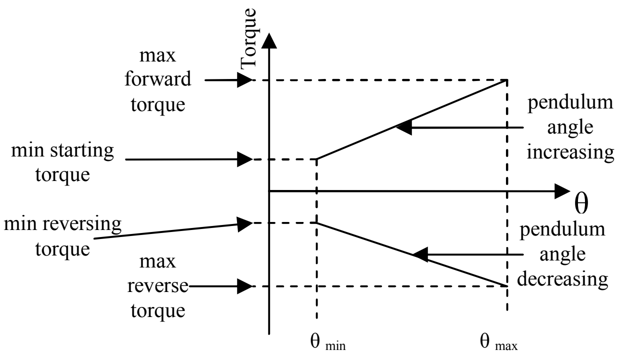

Fig 11 Torque profile

Initially, the pendulum starts with a minimum torque value at a minimum set angle. As the pendulum angle increases, the torque increases linearly until the maximum desired pendulum angle is reached.

The pendulum torque is related to angle by the equation:

$$T_m = \frac{TD_{max} - TD_{min}}{\theta_{max} - \theta_{min}} \times (\theta - \theta_{min}) + \theta_{min} \quad \ldots.(11)$$

Where TD_{max} is the maximum desired torque, TD_{min} the minimum desired torque, θ_{max} the maximum desired angle (triggers the pendulum to reverse direction), θ_{min} the minimum desired angle (triggers the pendulum to reverse direction), and θ is the current pendulum angle.

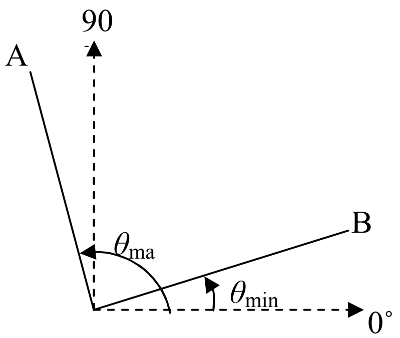

Fig 12 Pendulum angle related to torque (clockwise motion)

The pendulum increases its angle from point B to point A and the torque increases linearly from T_{min} to T_{max} according to (11).

When this maximum angle is reached, the torque profile is reversed and $-T_{max}$ is sent to the motor thus reversing the pendulum direction (figure 12)

The torque decreases linearly to $-T_{min}$ as it approaches point B. At this point the torque is reversed to $+T_{min}$ and the procedure repeats.

6. IMPLEMENTATION AND RESULTS

6.1 Reduction in network traffic

The system would work as anticipated for a few seconds, after which it would halt. Further investigation showed this was due to the flurry of back and forth network activity. The remote system was continuously transmitting its pendulum position, and torque values were being transmitted from the controller.

In order to remedy this, the network communication was reduced to only transmitting necessary data from the controller, i.e. when there was an update in the torque to output. This was achieved by having the host computer program continuously compare the current torque with the previous torque transmitted, if there was a difference, the new torque value would be sent.

This resulted in the system becoming stable, and it would run continuously without over burdening the network.

Another problem occurred was that the pendulum would occasionally go beyond its specified region and result in it crashing into the mechanical end-stops. It transpired that occasionally the torque data was not being updated quickly enough to control the pendulum even though the rate of the controller could handle this and so the speed of network transmission was investigated.

6.2 Network transmission speed

The controller and remote PCs were reprogrammed for a network speed test. The controller would send out a byte across the network to the remote PC and start a timer.

The remote PC was programmed to return this byte to the controller once it was received via the network. Once the controller received this byte it would stop the timer and display the round trip packet time graphically.

The results are shown in figure 13.

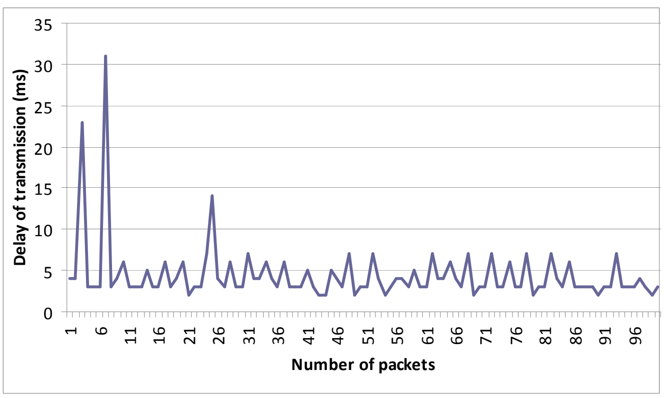

Fig 13 Effect of network delay as packets are transmitted

The results show that although the average time is 4ms, the delay can be longer, and can reach up to 31ms. This delay appears to be random and can result in erratic control as the sample rate is 10ms.

Methods of control with a varying delay time have been implemented (Goldberg et.al 1995, Shahidul et.al 2005, Antonelli 2006).

7. CART PROGRESS

7.1 Quantised torque control

The pendulum swing was erratic, sometimes hitting the end-stops and resulted in an uncontrolled behaviour of the cart. Since the torque was only updated three times per swing, and lost packets or network delay could result in this error. Figure 14 shows the pendulum angle (end-stops are at 0˚ and 200˚), and figure 15 shows the cart progress.

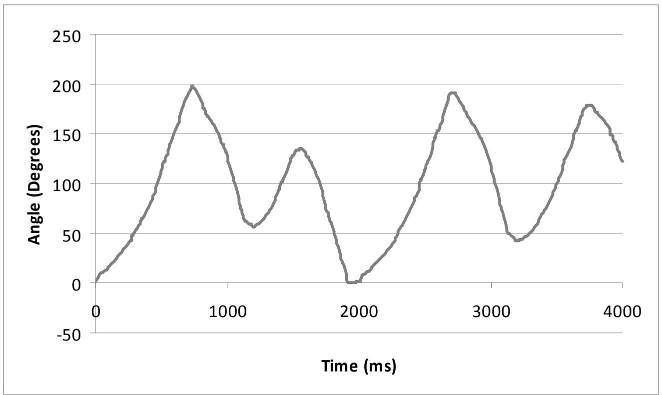

Fig 14 Resulting pendulum angle, quantised torque

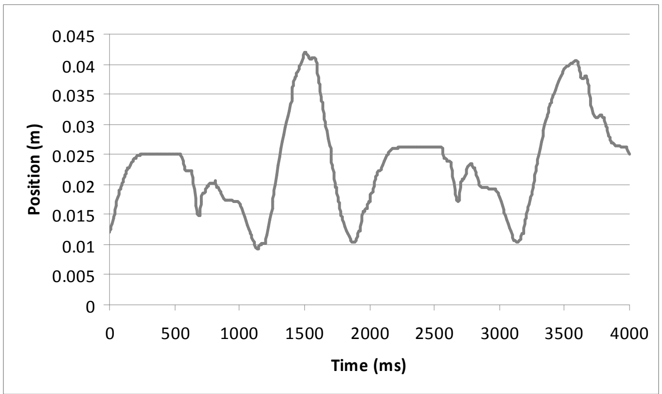

Fig 15 Resulting cart progress, quantised torque

The cart achieved some forward motion only to return to its starting point due to uncontrolled pendulum activity.

7.1 Continuous torque control

The cart progressed in the desired direction with a smaller amount of slip back (figure 17). This shows 8cm progress after 4 seconds. Greater control of the torque from the wireless PC with the ability to continuously update the torque as a function of the angle resulted in a stable pendulum swing and improved progress. Optimising the network traffic resulted in a stable pendulum swing as anticipated (figure 16).

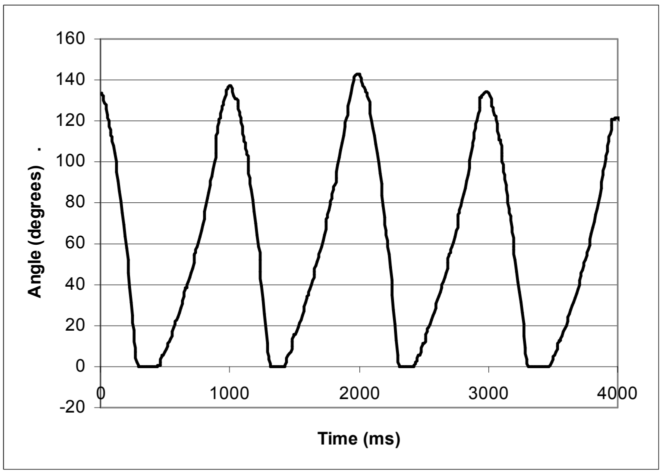

Fig 16 Angle position monitored by the host PC

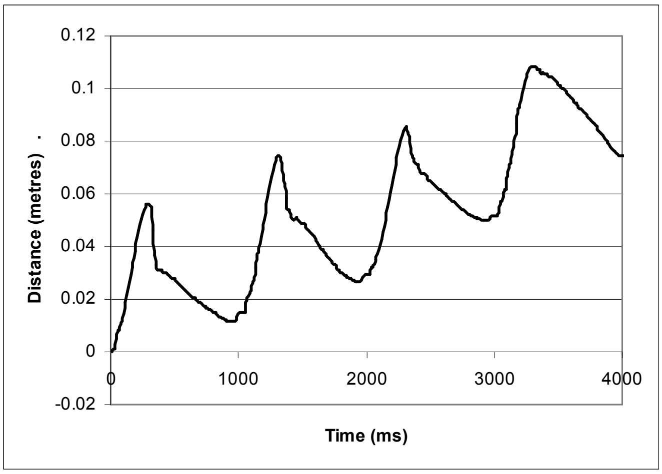

Fig 17 Cart progress monitored by the client PC

The added advantage of using continuous communication is that this torque function can be altered to achieve the desired displacement and velocity of the cart through modelling (Wane et.al 2007a).

8. CONCLUSIONS

The continuous transmission of data for a time critical system over a wireless network can result in instability. This was minimised by the use of procedures to reduce the network traffic to a minimum.

The advantages of having a host PC controlling the pendulum torque at a high sample rate was demonstrated in with the use of a torque function that was updated according to the pendulum angle.

Minimising the network traffic still didn't remove the problem of network delay on the system, this was measured over time and was shown to fluctuate. Occasionally, this delay was greater than the sample time and instability occurred. This was minimised by having a continuous torque control method allowing a complex torque pattern to be specified.

A solution to the fluctuating delay could be to have the remote PC process the time critical elements locally, the host only updates the torque function related to angle when necessary. This could be implemented on an embedded microcontroller system in order to increase the sample rate, however, the Ethernet would introduce a large overhead into the microcontroller in terms of extra programming and delay and so a proprietary wireless transmission protocol is suggested.

Improvements to the cart system could be the use of an accurate torque motor operating linearly rather than as a rotation.

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