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CONTROL OF THE RUTGERS ANKLE REHABILITATION INTERFACE

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ABSTRACT

This paper presents the control system development of the Rutgers Ankle rehabilitation device. The "Rutgers Ankle" is a haptic interface with a Stewart platform structure driven by six double-acting pneumatic actuators. Each cylinder input is controlled by one set of on/off solenoid valves. For overall system control, an interrupt handler loop is designed based on hardware interrupts. For precise flow rate control of the solenoid valves, a PWM scheme is proposed for a set of two on/off valves. The proposed PWM logic compensates the dead band of the valve response time. A distribution method for the desired pressure differential of the two air chambers of an actuator is proposed. The method is based on the minimization of the difference between the desired and measured pressure. During experiments, one actuator achieved a rise time of 90 ms and 0.3 mm resolution in an independent position control loop. The Rutgers Ankle has a 7 Hz mechanical bandwidth and allows stiffness control for haptic interaction during rehabilitation exercises. The measured performance is believed to be sufficient for ankle rehabilitation purposes.

1. INTRODUCTION

The "Rutgers Ankle" is a component of the *Telerehabilitation System with Virtual Force Feedback* project (Popescu et al., 1999) (See Fig.1). The "Rutgers Ankle" was developed to add a new rehabilitation device to the existing telerehabilitation system. It can move and supply forces and torques in six degrees of freedom (DOF) as required by ankle rehabilitation exercise scenarios. This haptic interface has been used successfully in orthopedic rehabilitation (Girone, et al., 1999), post-stroke rehabilitation (Deutsch, et al., 2001a), and rehabilitation of musculo-skeletal injuries (Deutsch et al., 2001b).

Figure 1 .The "Rutgers Ankle" Haptic Interface (Girone, et al., 1999). © ASME. Reprinted by permission.

The device is based on a Stewart platform architecture with double acting pneumatic actuators. The advantages of the pneumatic cylinders are high power-to-weight ratio, ease of maintenance, cleanliness, and the ability to maintain high forces without overheating. These qualities are especially valuable since the Rutgers Ankle is designed for the at-home-exercising rehabilitation. Noritsugu and Tanaka (1997) developed a therapy robot

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with two degrees of freedom. Their actuators were driven by Pulse Code Modulation (PCM) digital control valve, which is operated as an equivalent proportional valve with 8 ON–OFF valves for one actuator. Therefore, expansion to a multi-axis system for 6 DOF motion and force generation is expensive and bulky. Takaiwa and Noritsugu (1999) developed a haptic interface based on a pneumatic parallel manipulator. Their single-acting actuators are driven by a large and expensive electro-pneumatic proportional valve. Ben-Dove and Salcudean (1995) presented a new pneumatic actuator with voice coil flapper valves for use in teleoperation. The force was controlled through the differential pressure of two single acting actuators. Use of two actuators for one axis control makes the pneumatic system expensive and too large for home use.

On-off valves with multi-modular type design (such as the Matrix valve) make a multi DOF system cheaper and more compact than the servo valves mentioned above. Therefore, the Rutgers Ankle is actuated by high-speed on/off solenoid valves, which are driven by Pulse Width Modulation (PWM) logic. However, fine control of on/off solenoid valves is difficult because of the large valve response time and its discrete on/off nature. These valve characteristics must be considered in the control design to assure fast and reliable system response.

This paper describes the pneumatic control system of the Rutgers Ankle rehabilitation device. The following section gives an overview of the Rutgers Ankle haptic interface with emphasis on the valve configuration for each actuator. Section 3 presents the design of the interrupt handler loop for overall system control. Section 4 suggests a PWM approach for a set of two on/off valves. In section 5, the inner and outer pneumatic actuator control loops are presented. Section 6 describes the impedance control implemented for use in rehabilitation exercises. Section 7 concludes this paper.

2. THE RUTGERS ANKLE HAPTIC INTERFACE

Overall system description

The Rutgers Ankle control box is shown in Figure 2 (Bouzit et al., 2002). It outputs 12 air channels that drive the six double-acting actuators. Each of the 12 pressures is controlled by two solenoid pneumatic valves: one for intake and the other for exhaust. Seeking to maximize the haptic bandwidth, the interface MATRIX valves were specially chosen for their low response time (300 Hz) and high air flow (100 Nl/min). Sensors read the pressure in each of the actuator compartments. These signals are amplified and sent to an embedded PC (Pentium-233) via an A/D I/O card. These pressure values serve as inputs to the inner pressure control loop. The embedded PC outputs through the same A/D I/O board a control signal for each of the 24 pneumatic valves. These control signals specify the duty cycle of the PWM scheme.

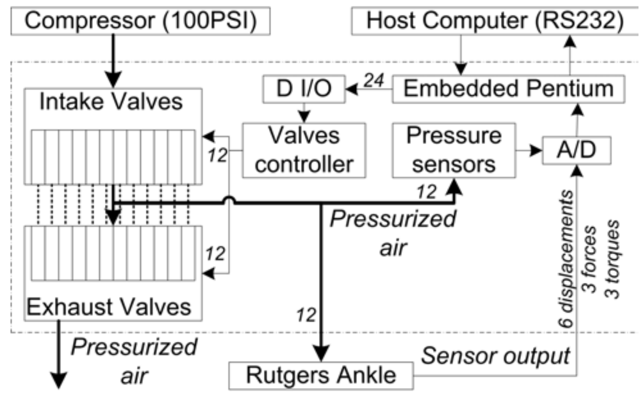

Figure 2. Rutgers Ankle Controller Overview (Bouzit, et al., 2002). © Rutgers University. Reprinted by permission.

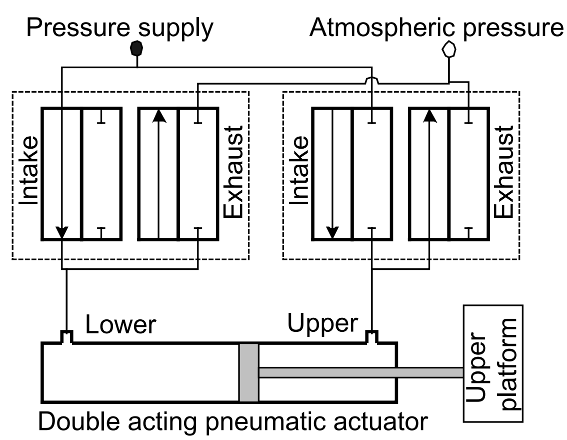

Figure 3. Valve Configuration for One Actuator. © Rutgers University. Reprinted by permission.

Valve structure

Each on-off valve is two–way such that two sets of valves can control the flow rate at each side of a double acting pneumatic actuator. Thus the on-off valves sets can have the following four states: "close-close," "open-close," "close-open," and "open-open." As shown in Figure 3, Valve L is pressurized by opening the intake valve and by closing its exhaust valve. Similarly, Valve U is depressurized by closing its intake valve and by opening its exhaust valve. The close-close state is used for holding the pressures and the open-open state is not used.

3. DESGIN OF THE INTERRUPT HANDLER LOOP

Task scheduling

The controller has two simultaneously executed loops: the main program and the timer interrupt handler. A hardware interrupt generated by one of the A/D I/O boards is used to insure exact timing. The interrupt handler executes the time-critical tasks, such as sensor readings, filtering and control. The main program does the rest of the tasks, mainly interfacing with the host PC over a serial port. Although the serial communication is not time -critical from the control point of view, it needs to run at a suitable speed to update the virtual environment frequently. The communication will stop whenever the timer issues a hardware interrupt. To avoid stalling, it is important that the time the handler needs to finish its tasks be as constant as possible. Having the work balanced across interrupts reduces the risk of having interrupts raised while the previous instance is still working. The work balancing is done by defining a number of sub-tasks and assigning them evenly to interrupts. Considering that the interrupt handler has to execute N tasks each having an occurrence period of T_k we compute T as the least common multiple of T_1, …, T_N. To achieve an even spread of the tasks we assign to each of them a starting interrupt (offset). These offsets are chosen to get the best distribution over the first T interrupts. Starting from the smaller periods to the larger ones, offsets are assigned to the tasks so that the maximum number of tasks in an interrupt is minimized. Table 1 shows the scheduling for pressure control of the Rutgers Ankle platform. The columns show the tasks while the rows show the interrupts. An "X" symbolizes the assignment of a task to an interrupt. The *duty-cycle-update* task has a period of 1; the *read-sensors* task has a period of 7; and the *cylinder-control-input* task has a period of 28. After scheduling, every interrupt executes at most two tasks.

Interrupt Interval Determination

The proper interrupt frequency needs to be selected in order to guarantee a proper functioning of the system control. The interrupt interval can be determined based on the frequency of the on/off valves and the resolution of the PWM signal, as well as on the computational amount of the interrupt handler. Among the tasks that need to be executed in the interrupt handler are: sensor reading, data filtering, pressure control and position control.

For good control performance, PWM frequency should take into account the solenoid valve characteristic response time and airflow. Based on the technical specifications, the solenoid valves can achieve a maximum on/off frequency of 300 Hz. A higher PWM frequency may overheat the valves reducing their lifetime due to excessive wear. Even a PWM frequency of 300Hz can cause valve overheating. However, the pressure transient

Table 1. Example of Work Scheduling. © Rutgers University. Reprinted by permission.

INTR	Duty update	Read sensors	Cylinder control input					
			1	2	3	4	5	6
1	X	X						
2	X		X					
3	X			X				
4	X				X			
5	X					X		
6	X						X	
7	X							X
8	X	X						
9	X							
10	X							
11	X							
12	X							
13	X							
14	X							
15	X	X						
16	X							
17	X							
18	X							
19	X							
20	X							
21	X							
22	X	X						
23	X							
24	X							
25	X							
26	X							
27	X							
28	X							
29	X	X						
30	X		X					
31	X			X				

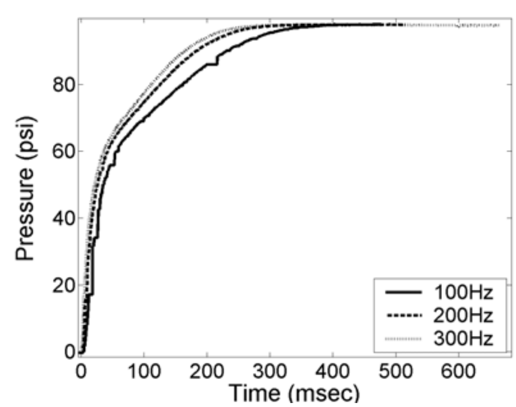

Figure 4. Pressure Transient Response With Respect To The PWM Frequency. © Rutgers University. Reprinted by permission.

response graph in Figure 4 shows faster response for the higher PWM frequencies. After several experiments, 250 Hz was selected as the best choice between better performance and longer valve lifetime. Finer resolution of the PWM will generate finer control input. But the interrupt intervals must be long enough for the handler to finish executing the controlling code. Otherwise, the controller will freeze. Considering task scheduling and PC speed, a duty cycle resolution of 1/28 was selected. Hence the interrupt interval is 4msec/28 or 0.1428 ms.

4. PWM LOGIC FOR A SET OF TWO ON/OFF VALVES

The dead band due to the finite valve response time (Figure 5) in opening and closing valves prevents a 100% PWM duty cycle. van Varseveld and Bone (1997) applied a novel PWM scheme for position control by using two standard 3-way solenoid valves. The proposed Rutgers Ankle PWM scheme for a set of two two-way on/off solenoid valves is similar. This PWM scheme is designed to remove the nonlinearities due to the open and close response time of the Matrix valves.

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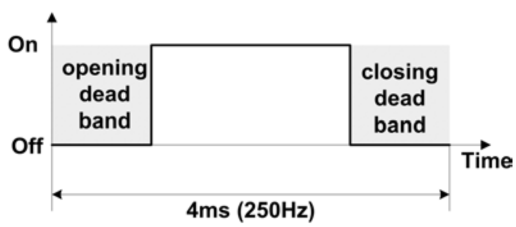


Figure 5. Dead band in a PWM Period. © Rutgers University. Reprinted by permission.

When using on/off solenoid valves to control the flow rate of the pneumatic actuator, the controller output must be resolved into the individual pulsing of the two valves. When control input **u** to the valve solenoid circuit is positive, the intake valve will be open and the exhaust valve will be closed. When control input **u** is negative, the intake valve will be closed and the exhaust valve will be open. Figure 6 shows the valve duty cycle (%) that can be achieved from a set of two on/off solenoid valves with dead bands. This figure shows that we cannot get the duty cycle below minimum possible cycle and above the maximum possible cycle. The minimum possible duty cycle d_{Dead} is defined as;

$$d_{Dead} = (T_v / T_{PWM})100\% \qquad (1)$$

where T_v is the valve response time (roughly 1ms) and T_{PWM} is the PWM period (4 ms).

It should be noted that if the duty cycle of either the intake or the exhaust valve is below minimum d_{Dead}, intake or exhaust valves will not open. Assuming that the opening and closing time of the valve are the same, the same size of minimum possible duty cycles are located at the valve opening and closing time as shown in Figure 5.

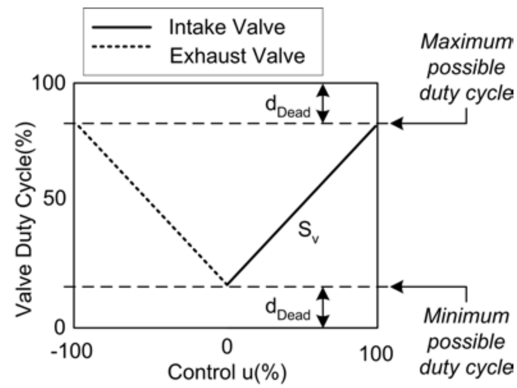


Figure 6. Achievable Duty cycle. © Rutgers University. Reprinted by permission.

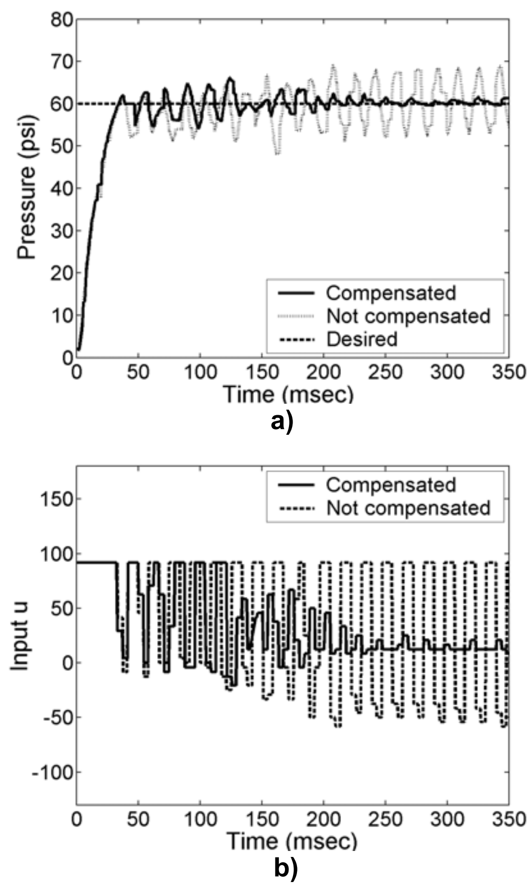


Figure 7. Dead Band Compensated PWM: a) pressure step response; b) duty cycle; © Rutgers University. Reprinted by permission.

In order to overcome the dead band, the control input can be mapped into the duty cycle as follows;

$$d_{max} = 100 - d_{Dead} \quad (2)$$

$$d = d_{Dead} + S_v u$$

$$S_v = \begin{bmatrix} (100 - 2d_{Dead})/100\ ; & u > 0 \\ -(100 - 2d_{Dead})/100\ ; & u < 0 \end{bmatrix} \quad (3)$$

where u is the desired control input, d is the applied control duty cycle, $d_{\max}$ is maximum applicable duty cycle, and S_v is the slope shown in Figure 6. Equation (3) compensates for the opening and closing dead band shown in Figure 5. Namely, even though the range of control input u is $0 \le u \le 100$, PWM duty cycle d will be located in the range of $d_{dead} \le d \le d_{\max}$.

Figure 7(a) shows the closed step response of the pressure with dead band compensated and without compensated dead band. Figure 7(b) shows duty cycle in each case. In the case of the dead band compensated PWM, the system is more stable, especially after 150msec.

5. CONTROLLER DESIGN

The Rutgers Ankle is controlled by an independent joint control strategy, which is composed of an inner control loop (pressure control) and outer control loop (position or force control loop).

The Inner control loop (pressure control)

The inner control loop divides the desired force differential that comes from the outer control loop into the desired pressure differential across the upper and lower cylinders. The desired pressure differential is generated considering the ratio of upper and lower cylinder areas and the minimization of pressure change from the current pressure.

The desired force differential Δf can be generated by independently controlling the pressures at each side of double acting cylinder as

$$\Delta f = A_l P_l - A_u P_u$$

$$= A_l (P_l - rP_u) = A_l \Delta P \qquad (r = \frac{A_u}{A_l}) \quad (4)$$

where A_l and A_u are lower and upper side area of double acting cylinder, respectively, $\mathbf{r}$ is the area ratio, and ΔP is the desired pressure differential. In order to generate the desired pressure differential as rapidly as possible, two errors of P_l and rP_u should be minimized.

$$e_l = P_l - P_{lm} \quad (5)$$

$$e_u = rP_u - rP_{um} \quad (6)$$

where e_l, e_u, P_{lm}, and P_{um} are the lower and upper pressure errors, and the measured lower and upper pressures. In order to minimize the pressure change from the current pressure, performance index J is defined as

$$J = |\Delta P - \Delta P_m|^{1/2} = e_l^{\,2} + e_u^{\,2} \quad (7)$$

$$= (P_l - P_{lm})^2 + (rP_u - rP_{um})^2$$

$$= 2Pl^2 - (2\Delta P + 2P_{lm} + 2rP_{um})P_l + \Delta P^2 + 2\Delta P P_{um} r + r^2 P_{um}^{\,2} + p_{lm}^2 \quad (8)$$

The partial differential of J with respect to P_l is zero at local minimum point as

$$\frac{\partial J}{\partial P_l} = 4P_l - 2(\Delta P + P_{lm} + rP_{um}) = 0 \quad (9)$$

The desired lower and upper pressures are then given by

$$P_l = \frac{P_{lm} + rP_{um}}{2} + \frac{\Delta P}{2} \quad (10)$$

$$P_u = \frac{1}{r}\left(\frac{P_{lm} + rP_{um}}{2} - \frac{\Delta P}{2}\right) \quad (11)$$

In addition, P_l, P_u must satisfy the boundary conditions

$$P_{critical} \le P_l, P_u \le P_s \quad (12)$$

where $P_{critial}$ and P_s are the critical and supply pressure, respectively. If P_l, P_u are less than $P_{critical}$, the intake pressure will be choked, which will cause flow saturation and limit controllability (Ben-Dove and Salcudean, 1995).

After the desired pressures are calculated by equation (10) and (11), a PI controller is applied for each desired pressures.

$$u_l = k_{pl} e_l + k_{il} \int e_l\ ,\ u_u = k_{pu} e_u + k_{iu} \int e_u \quad (13)$$

The control input determined by equation (13) will change the PWM discrete duty according to equation (3). Figure 8 shows the block diagram of the proposed inner pressure control loop.

The Outer control loop (position control)

The position control of each actuator is done as follows;

$$\Delta L = (L_c - L_m) \quad (14)$$

$$\Delta P = (K_p + K_d s)\Delta L + G_p \quad (15)$$

where L_c and L_m are the commanded and measured cylinder displacements, K_p, K_d are proportional and derivative gains, respectively, and G_p is the gravity compensation term of one actuator for moving actuator and platform mass.

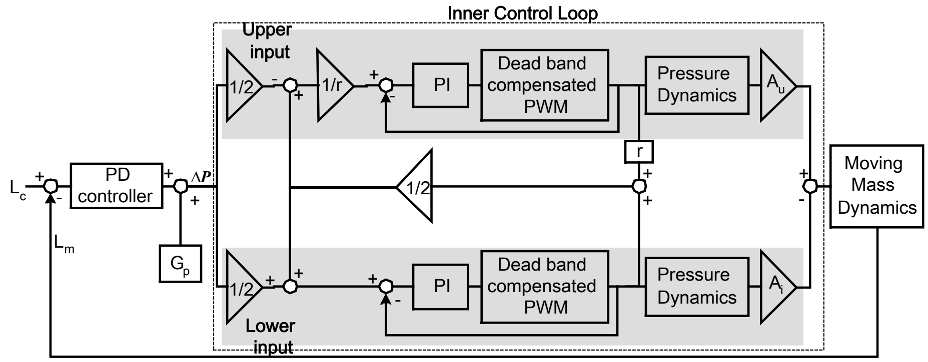
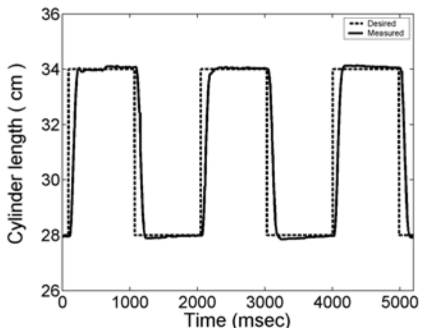
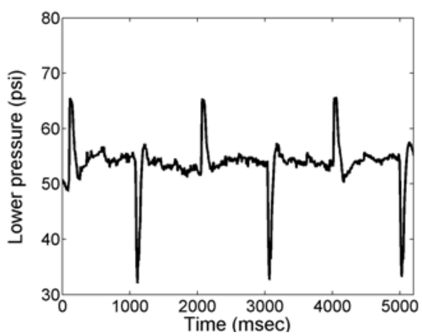


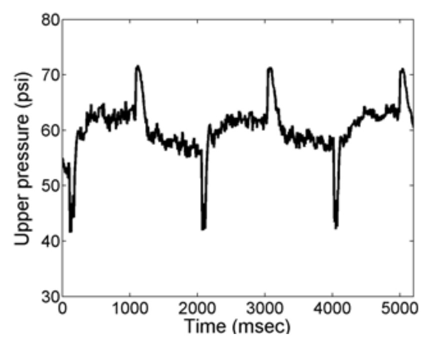
Figure 8. Joint Position Control of Each Actuator. © Rutgers University. Reprinted by permission.



a)



b)



c)

Figure 9. Position Control Results: a) displacement; b) lower pressure; c) upper pressure; © Rutgers University. Reprinted by permission.

Figure 9 shows the experimental results of independent joint position control. Figure 9(a) show that outer loop position control is successfully implemented without overshoots and with fast response about the rise time of 90 ms. The rise time of this pneumatic actuator with pressure feedback and two sets of 2-way valves at each part of the double acting actuator is twice as fast as the pneumatic system controlled by the 3-way solenoid valves described in van Varreveld and Bone (1997). Figure 9 (b) and (c) show the response of the lower pressure and upper pressures, respectively. Each pressure is changing with minimum difference change from current pressure.

By using independent joint control, we can control the posture of the Rutgers Ankle interface. Experimentally, it was determined that the pitch angle of the Rutgers ankle can follow a 7 Hz sinusoidal input as shown in Figure 10. The other axes have similar response. This speed is thought to be sufficiently fast enough for rehabilitation exercise purposes.

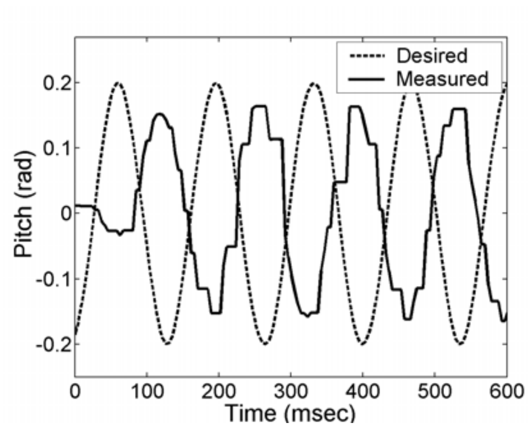


Figure 10. Rutgers Ankle Bandwidth (pitch angle). © Rutgers University. Reprinted by permission.

6. REHABILITATION CONTROL USING THE RUTGERS ANKLE

This section presents a rehabilitation exercise scheme using the “Rutgers Ankle” interface. Our platform can be applied for creating exercises training the flexibility, strength and balance of the subjects. Strength exercises are similar to conventional weight-training exercises. Patients move their feet as the device applies resistive forces. Flexibility exercises involve improving the patients’ range of motion by performing repetitive movements near their current range limits with little or no opposing forces. Balance exercises may require the simultaneous use of two mechanical devices, one for each foot. The large variety of exercises will allow patients immediate access to many different forms of rehabilitation through a single system. In order to generate these exercise types, a position based impedance control is applied as shown in Fig. 11.

The difference between the desired foot position X_d for rehabilitation exercises (Cartesian Space) and the value of $\mathbf{X}_m$ generated by filtering the measured interaction forces and torques to satisfy equation (16) will become the desired independent joint position input after mapping by inverse kinematics (IK).

$$\boldsymbol{F} = \boldsymbol{K}\boldsymbol{X}_m + \boldsymbol{B}\dot{\boldsymbol{X}}_m \tag{16}$$

Force and position will be related as

$$\boldsymbol{F} = \boldsymbol{K}(\boldsymbol{X}_d - \boldsymbol{X}_{foot}) + \boldsymbol{B}(\dot{\boldsymbol{X}}_d - \dot{\boldsymbol{X}}_{foot}) \tag{17}$$

where $\boldsymbol{F}$ is a vector of the forces and torques on the Rutgers Ankle,

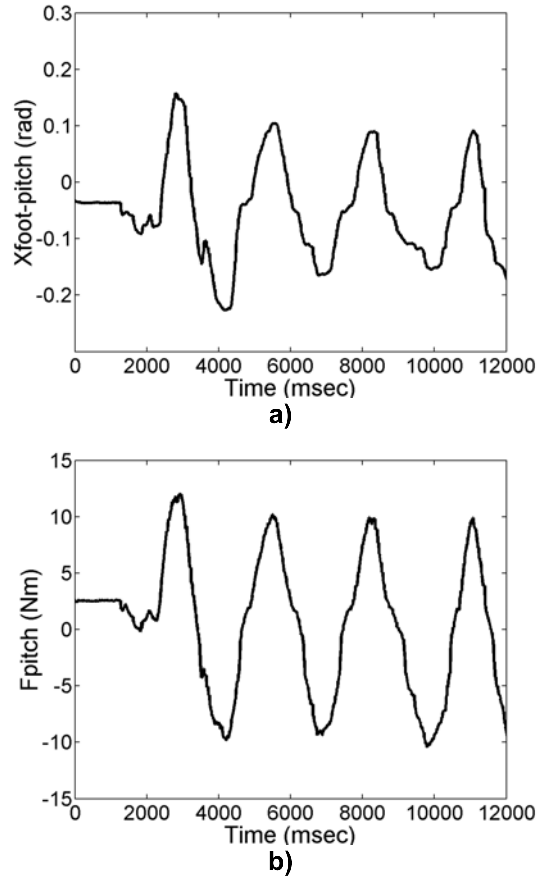


Figure 12. Plantar Flexion and Dorsiflexion Exercise with the Position Impedance Control: a) X_{foot} (pitch axis); b) F (pitch axis); © Rutgers University. Reprinted by permission.

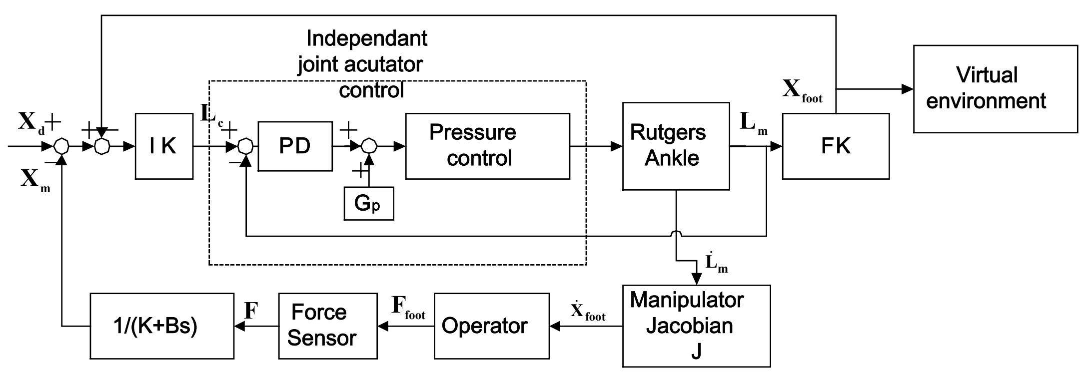


Figure 11. Impedance Control Block Diagram for Rehabilitation Exercises. © Rutgers University. Reprinted by permission.

$K =$ diag$\{K_x, K_y, K_z, K_{pitch}, K_{roll}, K_{yaw}\}$ is a stiffness matrix, $B =$ diag $\{B_x, B_y, B_z, B_{pitch}, B_{roll}, B_{yaw}\}$ is a damping matrix, and the $\mathbf{X}_{foot}$ is the measured foot position of a patient attached to the Rutgers Ankle. The $\mathbf{X}_{foot}$ will be used to manipulate the object in the virtual environment. If $\mathbf{X}_\mathbf{d} - \mathbf{X}_m$ is ideally equal to $\mathbf{X}_{foot}$, the desired impedance in equation (17) can be achieved.

Figure 12 shows the strength exercise for ankle plantarflexion and dorsiflexion based on the impedance control. In this experiment, $X_d = 0$ and the stiffness K_{pitch} was 50 NM/rad. With this impedance control, we can manipulate the level of the strength exercise by changing the stiffness and damping according to the patient condition.

7. CONCLUSION

This paper presented the pneumatic control system development for the Rutgers Ankle rehabilitation device. A PWM scheme for a set of two 2-way solenoid valves can precisely control pressures with flow rate control. The independent position control achieved a rise time of 90 msec with mass of pneumatic system and platform. This response time is faster than previous research results reported for 3-way solenoid valves. Based on position control of pneumatic system, position based impedance control was implemented in order to generate exercise types according to the patient condition. Thus cheap and compact solenoid valves allowed a 6 DOF ankle rehabilitation device to achieve precise response at about 7Hz bandwidth. Future research involves the implementation of task-level haptic effects necessary in the rehabilitation simulations

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