Design and Control of a Reconfigurable Bed/Chair System with Body Pressure Sensing

by

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Abstract

A reconfigurable chair/bed system has been developed to supplant manual labor associated with the transfer of bedridden patients from the bed to a wheelchair, and allow for postural freedom within the chair to more comfortably execute household routines. In addition, a particular reconfiguration scenario has been chosen and executed to demonstrate machine understanding of human postural preference and successful adjustment of control parameters to match that preference.

The design of a five degree of freedom reconfigurable chair/bed allows for a wide range of control possibilities over patient posture and support. The initial objective chosen for study is the control of the back leaf of the chair/bed to control position of the human trunk. Specifically, for a given posture the preferred human state is one that requires a minimum amount of muscle exertion to maintain this state. A method for measuring human exertion by external sensors and a control method to reduce this exertion is presented.

Interpretive control has been proposed as a control methodology that introduces a floating reference point that moves to relieve muscle exertion as the human changes position. An interpretation element has been included as a high level controller that takes in the raw force data and processes it to generate specific control commands that adjust the static reference point of the backleaf of the chair while actively controlling the dynamic behavior. Issues concerning the stability of this control algorithm are studied. In addition a study of how altering parameters will affect human comfort in the chair are studied by examining response characteristics.

Thesis Supervisor: Haruhiko H. Asada
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Chapter 1
Introduction

1.1 Problem Statement

The rapid increase in the elderly population worldwide is a critical problem faced by today's society. Effective technologies for elder care are badly needed to relieve costly, manual, labor intensive care strategies employed in hospitals and nursing homes today. A home-based health care system that incorporates physical assistance by intelligent machines offers a promising and realizable solution to the growing challenge ahead.

To realize the use of intelligent machines as servants in the home environment to people in need of assistance, many questions concerning the relationship among design, control, and the human being served must be answered. Clearly, a vulnerable human relying on a machine for support in the home environment requires a level of human-machine symbiosis that has yet to be realized. It is no longer possible for the human to understand and adapt to the machine to ensure a successful relationship. On the contrary, in this situation the machine must understand the human. Beyond understanding, the machine must also be capable of adapting to human preferences to achieve the most comfortable relationship possible.

For this concept to become reality, machine design, control, sensing, and understanding of human preference must all be coordinated to achieve success in a variety of physical assistance scenarios. First, systems must be designed to be flexible and capable of providing assistance in a variety of home scenarios. In addition control system design must be focused on identifying and realizing the physical arrangement and level of assistance most preferred by the human. Among the most critical research issues is how to extract the preference of the human in a non-invasive manner that yields consistent, accurate results. Specifically, an appropriate interpretation scheme must be conceived that can directly translate measured data to specific control objectives that can be carried out by a more traditional machine control routine. These control objectives must agree with the physiological preference of the human and all control parameters that affect the physical human-machine interface must be tuned to achieve this goal.

1.2 General System Goals and Requirements

To begin to understand more specifically what daily activities of the elderly offer the greatest opportunity for implementation of physical assistance, site visits to various elderly care facilities were made. Many useful pieces of information were revealed in those visits. For instance, more than 80 percent of the elderly residing in nursing homes or hospitals decided to do so primarily because they could no longer be treated at home after having been left permanently bedridden. This illustrates that many elderly patients are capable of living at home comfortably with the exception that they have mobility difficulties. Related activities include physically interacting with the commode. By wide consensus among the elderly, care practitioners and advisors in its most general form the first machine prototype should be able to offer physical assistance in the following areas:

- Bed/Chair Transfer
- Bedsore Prevention
- Commode Difficulties

- Standing from Sitting Position

In addition to the functional goals, general system requirements that address the user's perspective are required. These requirements can be placed into two categories:

- Patient Safety
- Patient Comfort

The system must provide freedom to the patient in a manner that keeps the patient comfortable and safe at all times. This implies an understanding of each patient's definition of comfort and successful translation of this understanding to the design and control of our system. It is in this area that new research developments are needed. Design of the mechanisms, sensors, and controls must be approached as one integrated system to achieve patient safety and comfort. Safety is the first high-level control priority, but after satisfying all safety considerations, a successful control strategy must optimize human comfort. The primary safety considerations include monitoring body position and configuration on the chair to ensure that any impending actuation does not pose a threat of physical harm to the human body. For example, if one of the patient's arms were to slip into a position where reconfiguring the chair could cause pinching of the limb, the system must be aware of this fact and halt progress until the condition is rectified. Sensors must be included in the design of the chair surface that can detect pressure normal to the surface and also tangential to the surface. This information can be used to establish a series of safety checks that must be passed before action is taken.

The same sensory information that guarantees patient safety can also be used to interpret patient comfort. If skin shear or pressure becomes too high at some particular configuration it can be reasoned that this configuration is unacceptable and should be avoided if possible. For example, while transitioning from a seated to standing position, the multi-DOF chair system offers a wide range of possible trajectories to achieve that goal. By measuring the skin shear and pressure patterns for any number of trajectories, the trajectory can be chosen that minimizes skin pressures, thus providing maximum comfort.

It is evident that machine design, sensor design, and controller design must all be integrated to achieve the functional and system goals agreed upon for success in the home-health care arena.

1.3 Objectives of Thesis

This thesis describes a new technology for home-based elderly care focusing on mobility assistance for bedridden persons. This new system illustrates the design of a machine, sensors, and controller that offers a specific service to the human in a safe and comfortable manner. A reconfigurable chair/bed system has been developed to supplant manual labor associated with the transfer of bedridden patients from the bed to a wheelchair, and allow for postural freedom within the chair to more comfortably execute household routines. This thesis details the concept formulation and detailed design of a reconfigurable bed/chair that solves the bed/chair transfer problem and gives a wide variety of position and support options to improve patient comfort. In addition this thesis details a new implicit human-machine communication scheme that includes a digital interpreter and active sensing to infer human desire to change configuration by motion augmentation. A method for tuning control parameters is presented that illustrates how adjustments in the characteristics of the controller affects human interaction with the chair. Parameters are chosen that allow the human to interact and communicate with the chair with the least amount of muscle exertion and the most comfort within the stability limits of the aggregate human-machine system.

The design of the five degree of freedom reconfigurable chair/bed allows for a wide range of control possibilities over patient posture and support. The initial, specific control objective that has been chosen for study is the admittance control of the back leaf of the chair/bed to control position and stiffness of support of the human trunk. Specifically, for a given posture the human should have to exert a minimum amount of muscle force to maintain this state. Measurement of the level of human muscle exertion becomes a critical challenge. In this thesis, a method for measuring human exertion by external sensors and a method of control to reduce this exertion is presented.

Chapter 2

Physical System Concept Development

2.1 Functional Specifications

To begin to make an effective evaluation of human comfort with respect to those parameters that can be affected by the bed/chair system the system must be able to conform to all reasonable body configurations, generate a wide range of coordinated motions and speeds, and maintain physical stability. These criteria establish the necessary functionality of the mechanism to be designed.

To achieve the system requirements of patient safety and comfort, sensory information indicative of these qualities must be provided. The machine must be instrumented to measure physical quantities that when incorporated into the system controller can provide the necessary indication of patient safety and comfort. Of course the system controller design must be carefully considered to have the ability to properly interpret sensor information and generate the appropriate control action.

2.2 Assessment of Current Technology

Currently mobility assistance for the elderly is addressed using manual manipulation of the patient by care practitioners. Transferring the bedridden from a bed to a wheelchair is an extremely laborious, physical job, which, for average people without the use of special equipment, is difficult to perform. A variety of equipment for lifting the bedridden has been developed and deployed at both hospitals and homes. In some cases manually controlled mechanical devices are utilized. These include a host of mechanical lifts or hoists that use a harness to grasp the patient and a manually operated hydraulic system to provide the manipulation effort. Other types of transport equipment include sliding chairs and belt-conveyer beds. The transfer board is another method utilized in care facilities that involves no active mechanical manipulation. These systems are not well received by elderly patients. They suspend the patient, making them feel out of control and unsupported. In addition in many cases they apply high pressure at specific points that causes bruising and in more dramatic cases, breaking of bones at the point of contact.

Clearly the methods of physical assistance for the elderly in care facilities and in the home are based heavily on direct assistance from several care practitioners with the possible aid of a simple manually operated mechanical device with a single functionality. There are no devices in existence that utilize automation or active sensing. In addition there are no mechanisms that offer multiple functionality from an integrated system. With this in mind there is no precedence for our work, only a set of problems that we would like to solve using an integrated system design approach.

2.3 Rail System Design Concept

Two versions of a rails system design concept are illustrated in Figures 2.3.1 and 2.3.2. These two figures illustrate different kinematic structures with the same physical assistance functionality. This system utilizes a mobile chair suspended from the ceiling. Many degrees of freedom are included, but require a track system to be included in the house to allow the human to move about freely. The suspended chair integrates into the bed to provide a no-transfer transition from bed to chair. The elaborate track system required to make this concept feasible is a major deterrent to further development.

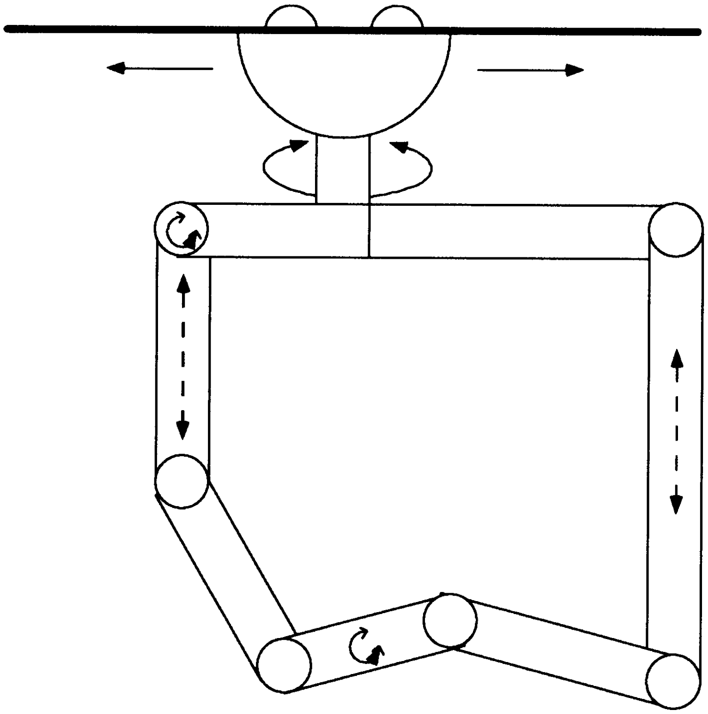


Figure 2.3.1 Closed Chain, Hybrid 8/4 Bar Linkage

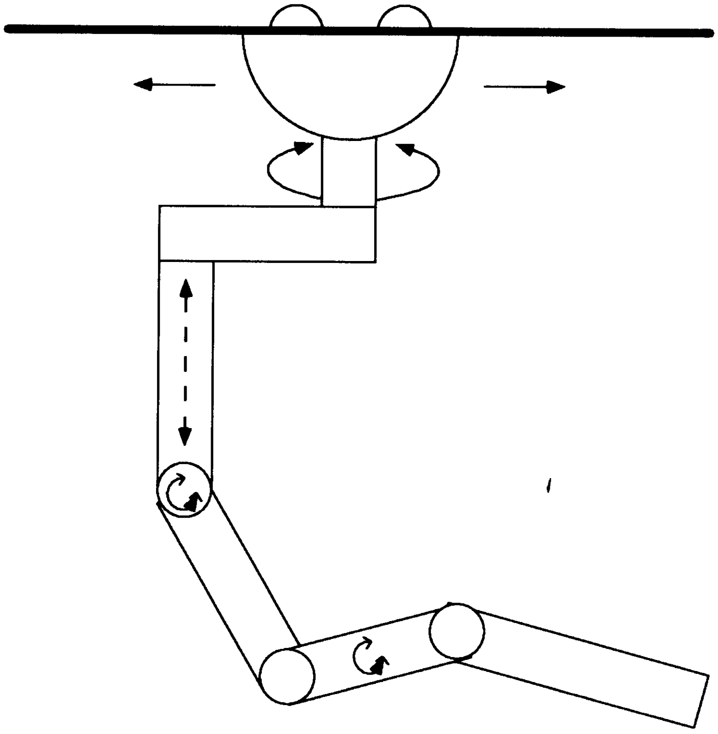


Figure 2.3.2 Open Chain, Center Mount

2.4 Wheelchair/Bed Concept

The need for transferring the patient between the bed and the wheelchair is eliminated by devising a hybrid wheelchair/bed system that serves both as a wheelchair and as a bed. When used as a wheelchair, the patient can take various sitting positions and move around freely within a house. When used as a bed, the patient can lie flat in a commodious space. The transition between the two modes, wheelchair and bed, can be performed easily and quickly without laborious operations. The reconfigurable chair/bed concept supplants human exertion with mechanical actuation and intelligent control. The approach is a unified solution to these problems created by taking a system level perspective of the desired functions. Figures 2.4.1, 2.4.2, and 2.4.3 show schematics of a hybrid wheelchair/bed system consisting of a reconfigurable chair and a U-shaped bed. The reconfigurable chair can move from a lying position to a seated configuration in one smooth motion back actuating the appropriate leaves of the chair.

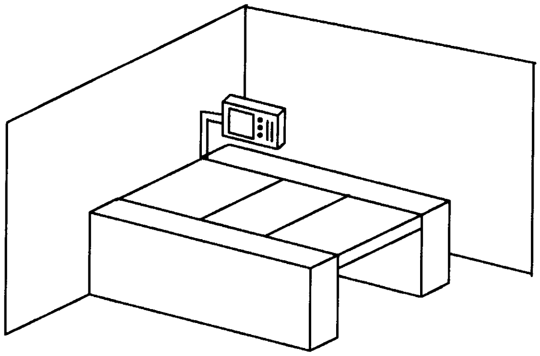


Figure 2.4.1 Schematic of Hybrid Chair/Bed System in Lying Position

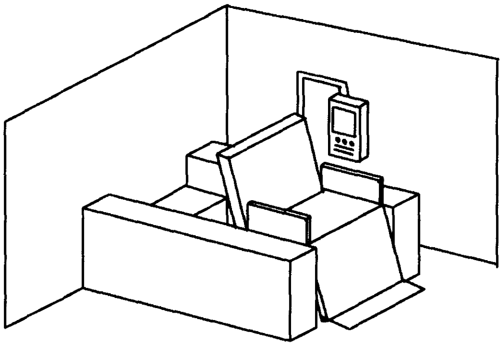


Figure 2.4.2 Schematic of Hybrid Bed/Chair System in Seated Position

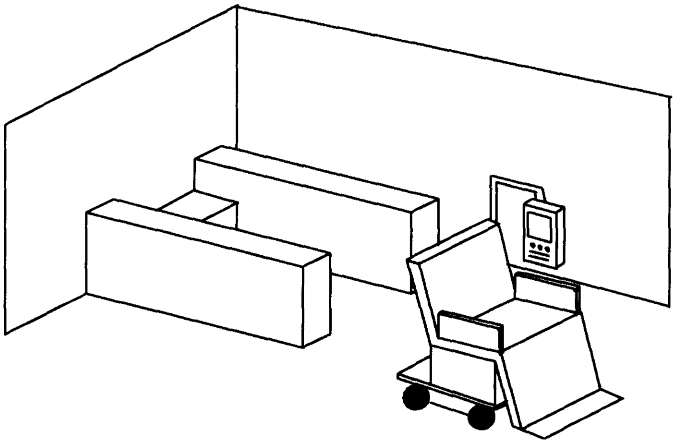


Figure 2.4.3 Schematic of Hybrid Bed/Chair System in Transit

The wheelchair can be detached from the bed for the transport of the bedridden person, and docked to the bed for sleep. The transition can be made while the patient is lying in the bed. The chair is reconfigurable so that it can be a flat bed or a couch with a reclining back with a foot rest. The wheelchair is narrow enough to maneuver freely within a crowded room, while the bed is wide enough to prevent the patient from falling out and roomy enough to provide comfort.

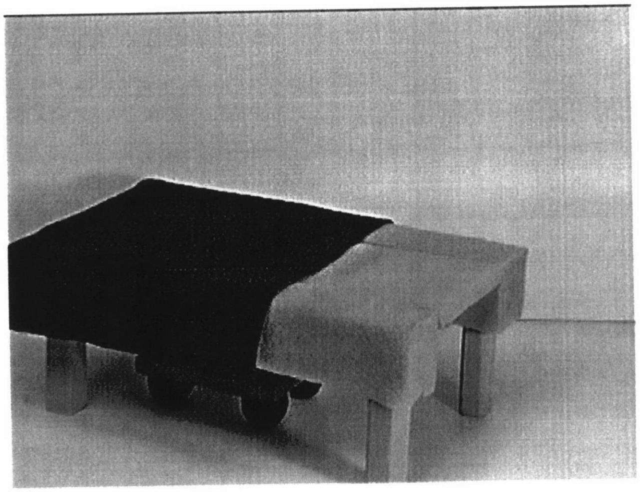


Figure 2.4.4 Foam Model of System in Lying Position

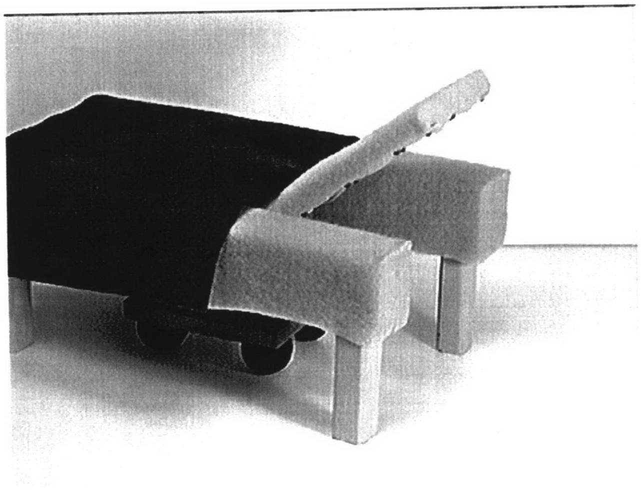


Figure 2.4.5 Foam Model of System while Reconfiguring

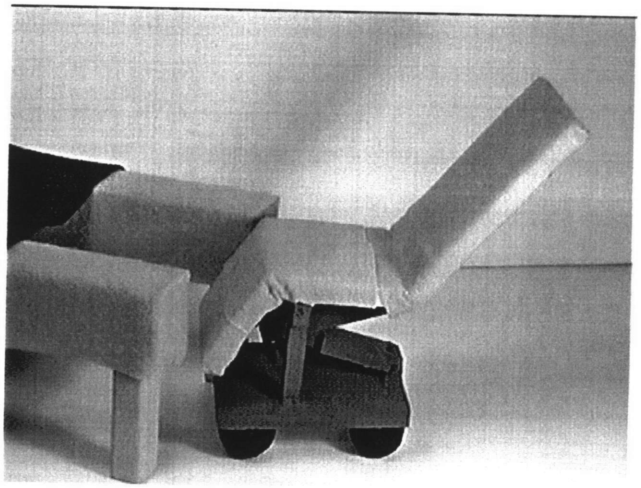


Figure 2.4.6 Foam Model of System in Seated Position

Figure 2.4.4 shows the wheelchair/bed system in the docked bed configuration. To detach the wheelchair from the bed portion, the back of the chair is first raised half-way through the position shown in Figure 2.4.5; then the whole body of the chair is slid off from the end of the bed portion and the foot rest is folded down, as shown in Figure 2.4.6. Finally, collapsible arm rests are raised (not shown in figure). To move the chair back to the bed configuration, the procedure is simply reversed.

The reconfigurable bed/chair system is comprised of three major elements: the human being, the actuated mechanism, and an extensive array of sensors. The objective is to fully understand the detailed relationship among these elements to clearly define for a particular system, what states are observable, what control objectives are achievable, and how to optimally reach these goals. Specifically we want to realize the full potential of the unique sensing and actuation ability of the reconfigurable bed/chair system to promote elderly patient safety, health, and enhancement.

The closed loop control of the reconfigurable bed/chair system is an example of the intimate cooperation that must exist among the three elements to reach the desired objective (Figure 2.4.7).

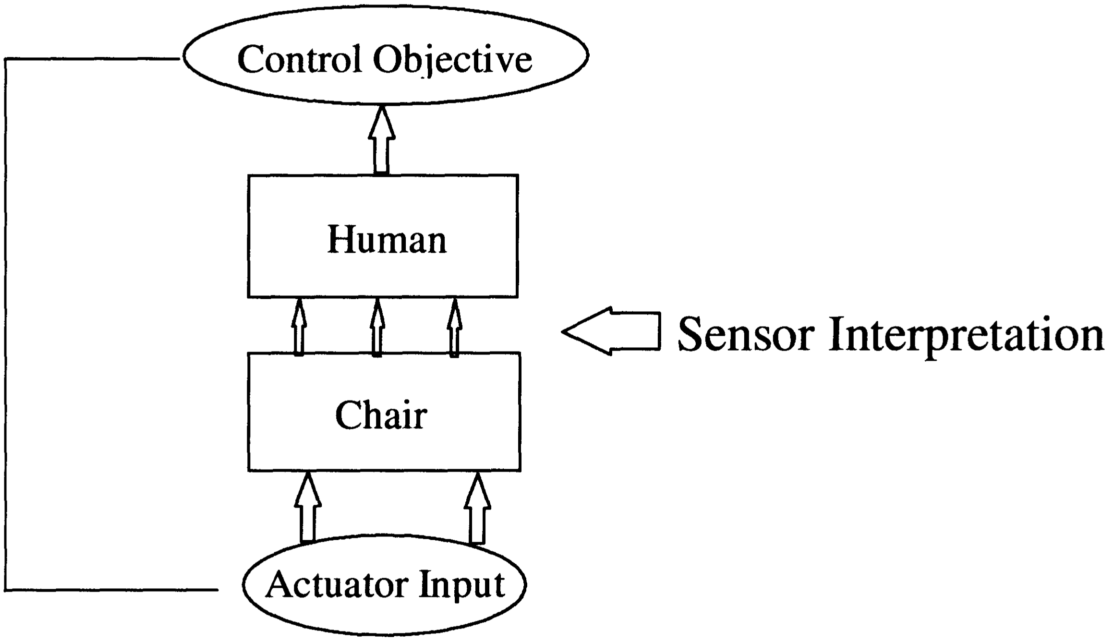


Figure 2.4.7 - Reconfigurable Bed/Chair System Structure

Dynamic models of the bed/chair mechanical system can be formulated that can be utilized to tailor machine performance to desired specifications. However, our desire is to monitor, and at times control the status of the patient. With this in mind a clear understanding of the causal relationship between the machine and human is necessary. Because the human is not rigidly linked to the mechanical system, a one to one relationship between bed/chair configuration and human body configuration does not exist. To resolve this issue pressure sensor data extracted from an array of sensors mounted to the chair/bed pad surface must be processed to yield a good estimate of the relationship between the human and the bed/chair. With this estimate, a simplified human model provides output values for parameters that we wish to control. These values can then be processed by the controller to establish new system inputs that will move the system toward convergence about the performance objective. This is illustrated in Figure 2.4.7.

Active posture control is an example of one possible function made possible by this human-machine-sensor integration strategy. For example the chair frame can be reconfigured to move a patient through sitting, lying, reclining, and standing positions. Also these same actuation abilities allow for a certain amount of local posture control. In addition the frame can be servoed to apply a specific impedance to human motion. Control over this impedance has applications in patient exercise for maintenance and rehabilitation of joint and muscle strength and range of motion. All of these diverse control objectives are possible with adjustments in controlled parameters of our highly flexible, integrated human-machine-sensor system, not modifications of mechanisms. Previous work has emphasized pressure measurement and equilibrating pressures. [Brienza, 1996]

Sensor data is a key feature of the bed/chair system. This data can be processed to estimate a number of human activities and physiological status for both patient monitoring and machine control applications. Some examples are listed:

- Respiration rate can be deduced from low frequency oscillations in the pressure detected in the human trunk region.
- Frequency of body position reconfigurations on the chair/bed surface can be used as an indicator of the comfort of the patient during sleeping or waking hours.
- Particular body configurations can be detected that indicate postures that could place the patient in danger of injury.

- Classification of posture patterns over time can lead to insight into personal habits that may indicate health problems.
- Pressure sensor data can be used to provide feedback for impedance control of the bed/chair system for exercise and rehabilitation with nominal trajectory and impedance tuned to a specific human.

The 5-DOF bed/chair system offers a wide range of body trajectories to achieve a desired body position. Depending on the patient, different body positions and motion trajectories will correspond to a varying degrees of comfort for each individual. In addition the chair offers a diverse array of sensory data that can be tapped to interpret the level of human comfort and monitor patient status. A challenging aspect of this work is the use of this data to indicate human satisfaction with chair performance in a given physical assistance scenario and how this data can be used to suggest changes in system behavior that will offer the human a higher level of comfort.

Chapter 3

Detailed Design of Five Degree of Freedom Reconfigurable Bed/Chair System

3.1 Kinematics and Workspace

To achieve the desired functionality described in the previous section a 5-DOF robotic chair has been designed. The chair features independent vertical and rotational degrees of freedom of the chair seat. In addition the back support and leg support leaf are independently actuated. The chair also features arm, leg, and neckrests to increase the comfort and support of the patient. The entire chair can be moved fore and aft by a fifth independent degree of freedom that is actively controlled to maintain balance over the vehicle platform upon which it will be mounted.

All together the chair is capable of assuming an infinite number of configurations ranging from standing up with a seat angle of 60^{o} (Figure 3.1.3) from horizontal to a reclined seat position of 30^{o}. The seat can move vertically 6" to adjust to various bed levels (Figure 3.1.1). Together the independent degrees of freedom can be coordinated to achieve among others, a reclined, seated, standing, and lying positions. The lying configuration is shown in Figure 3.1.1. The seated position is shown in Figure 3.1.2. The standing position is shown in Figure 3.1.3. Independence of the vertical and rotational degrees of freedom is achieved by a very compact five-bar kinematic linkage shown in Figure 3.1.3.

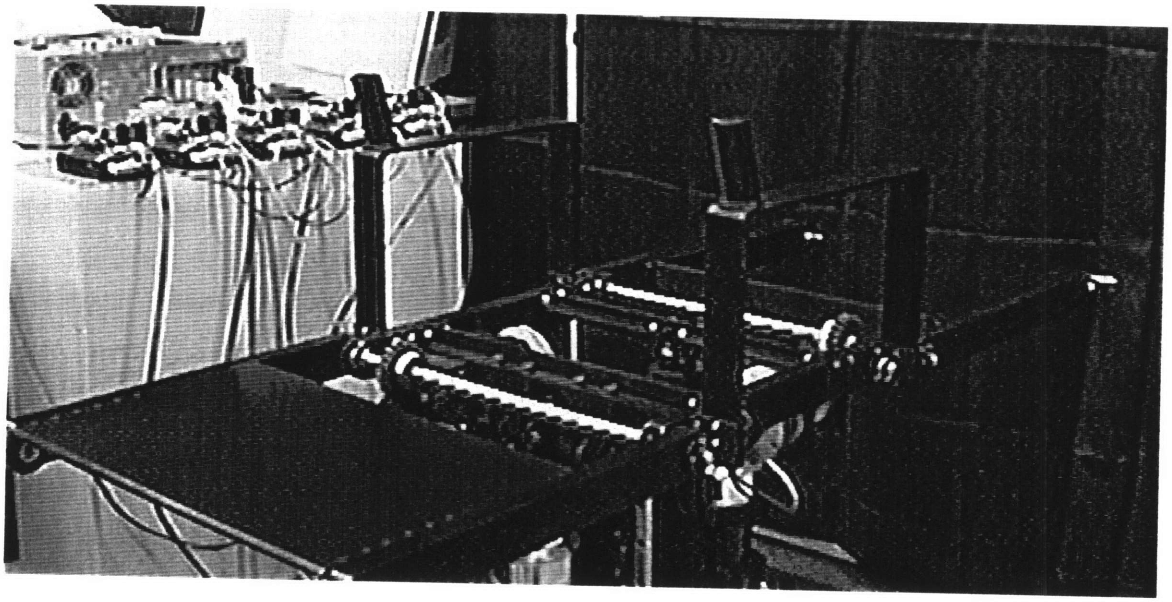


Figure 3.1.1 5-DOF Robot in Lying Position, Head and Neck Rests Retracted and Armrests Extended

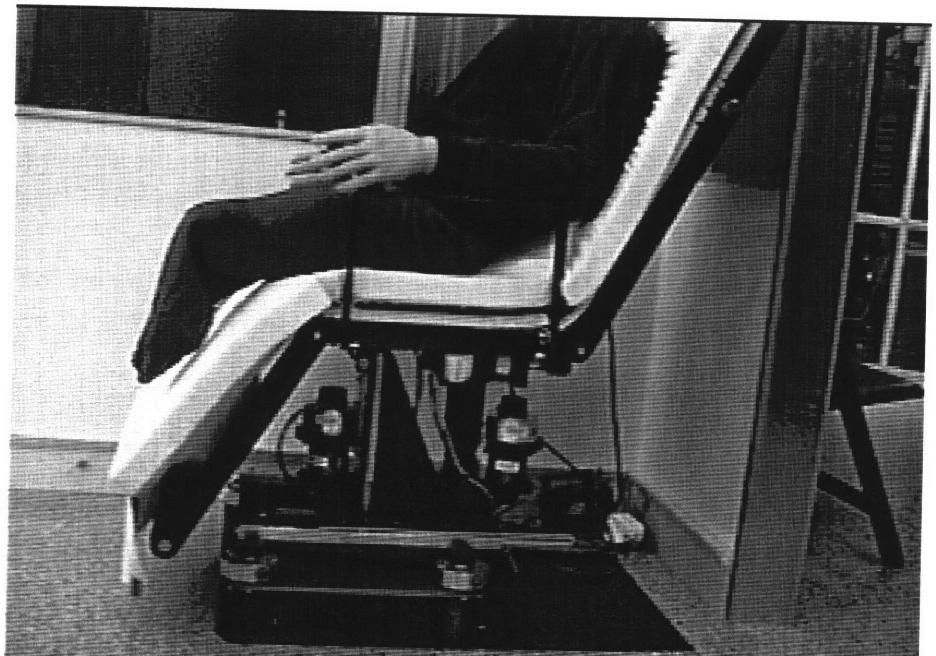


Figure 3.1.2 5-DOF Robot in Seated Position with Person Seated

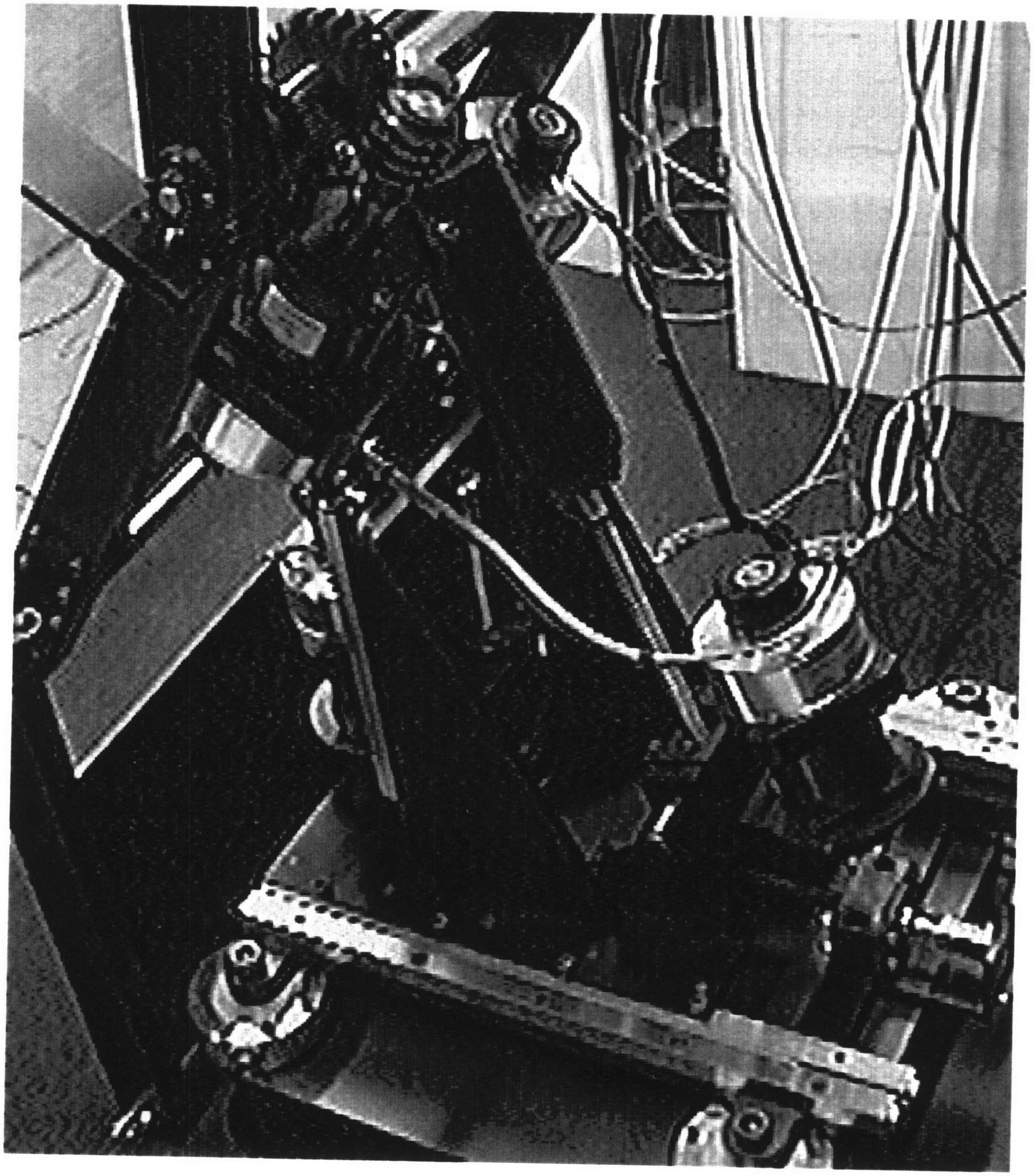


Figure 3.1.3 ,Detailed View of 5-Bar Kinematic Linkage and Actuation System

When designing the five bar linkage one must be aware of toggle positions particularly when working with a workspace as broad as that offered by the chair in such a compact mechanism. If a toggle position is reached the kinematic relationship becomes discontinuous and smooth control is not possible. Avoiding toggle positions was a top priority in the design of the kinematic structure of the chair/bed mechanism.

3.2 Actuator Assemblies

The seat vertical and rotational degrees of freedom are actuated by ball screw assemblies powered by DC servo motors. In addition the back and leg support sections of the chair are also independently actuated. These rotational joints are driven by DC servo motors via worm gear transmission. Both of these actuation assemblies are shown in Figure 3.1.3. The back and leg rests are actuated independent of the seat. DC Servo motors via a specifically designed spur gear and worm gear transmission arrangement provide power to move these joints. Prismatic actuators are utilized to reduce the extremely high torque loads that would be required to actuate the linkage by rotational actuators at the pin joints. These prismatic actuators are actuated by ball screw assembles driven by DC servo motors placed in parallel in a custom arrangement to conserve space.

3.3 Horizontal Compensation and Load Cells

To maintain physical system stability while maintaining as small a footprint as possible, the entire chair assembly has been placed over a custom designed horizontal linear slide that compensates to place the center of gravity of the chair and patient over the geometric center of the holonomic, omnidirectional vehicle. 12" of horizontal compensation has been designed into this system. A view of the load cells and linear slide is shown in Figure 3.1.3. The horizontal degree of freedom is used to maintain balance of the chair structure and the human over the holonomic, omnidirectional platform in one dimension. Utilizing data collected from four load cells fixed to the bottom corners of the chair the horizontal actuator is controlled to align the center of gravity of the load over the top of the geometric center of the holonomic, omnidirectional platform. In addition, in emergency scenarios, load cell data can also be utilized to predict an impending sideways tip-over condition and the holonomic, omnidirectional vehicle can be directed to compensate and resolve the condition.

3.4 Performance Specifications

Maximum actuator velocities are 1"/sec for linear actuators and 3 rpm for back and leg support sections. The system was also designed to carry the load of a 200lb patient. Appropriate gearing, transmission, and motor choices were made to handle the torque loads induced by the 200lb load. All actuation assemblies are constrained to handle the loads without excessive deformation of the structure of the robot while maintaining adequate gear engagement for the worm gears.

3.5 Platform Dimensions

The chair/bed dimensions were designed in accordance with established seat dimension values found in human factors literature. In addition the width of the bed/chair system has been specified at 22 inches to give plenty of room on the chair for the patient, but still allowing the chair to move freely through standard doorways in the home.

3.6 Retractable Arm, Neck, and Foot Rests

In the interest of safety the chair/bed was designed with manually actuated armrests, footrest, and neck rest shown in Figure 3.1.1. These were designed into the chair frame after consultation with medical professionals. It was advised that in order to maintain patient safety, these safeguards must be included in the design to keep appendages of the patient from colliding with the environment while the chair is static or moving. Appropriate mechanical stops, rails, and supports are being included in the design to ensure the safety and comfort of the subject under evaluation.

Chapter 4

Detailed Mechanism Design of One Degree of Freedom Coordinated Chair/Bed

Two separate bed/chair prototypes have been designed, constructed, and tested at the d'Arbeloff Laboratory for Information Systems and Technology. The first prototype is a five degree of freedom mechanism that offers independent actuation of backrest, leg rest, and seat. The second prototype is a one degree of freedom coordinated prototype that coordinates the actuation of the footrest, neck rest, backrest, and leg rest. The seat remains fixed and the other four joints move in a coordinated manner from a lying flat position to an upright seated position. The seated position is shown in Figure 4.2 and the lying position in figure 4.1.

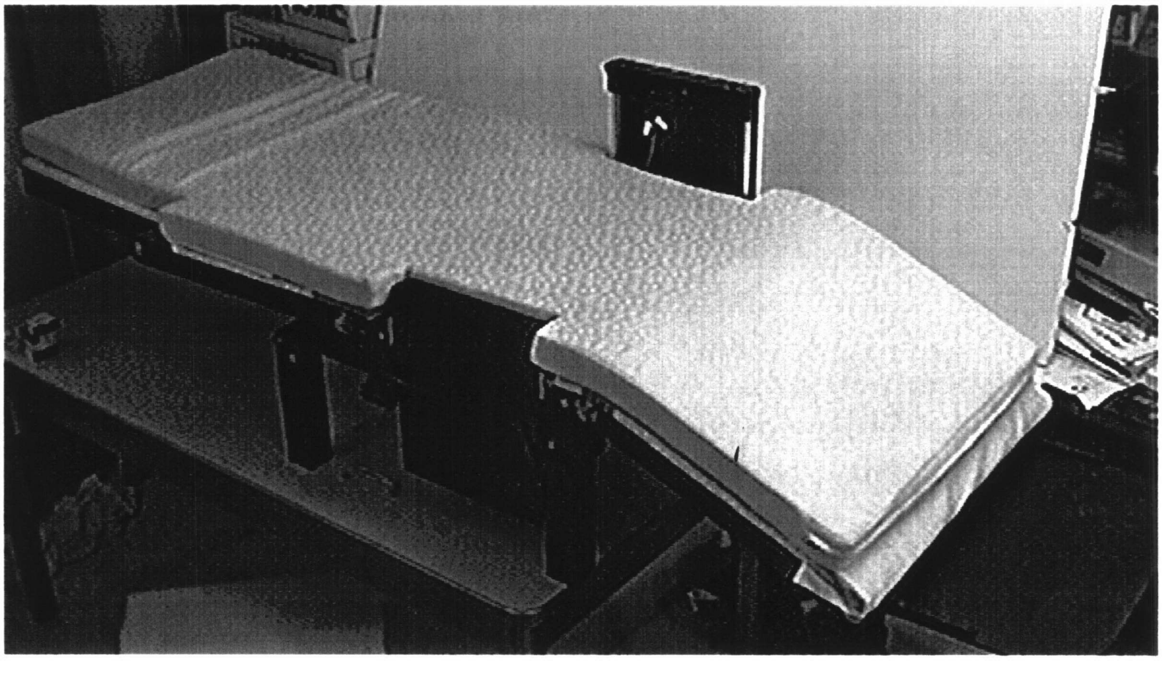


Figure 4.1 1-DOF Bed/Chair in Lying Position

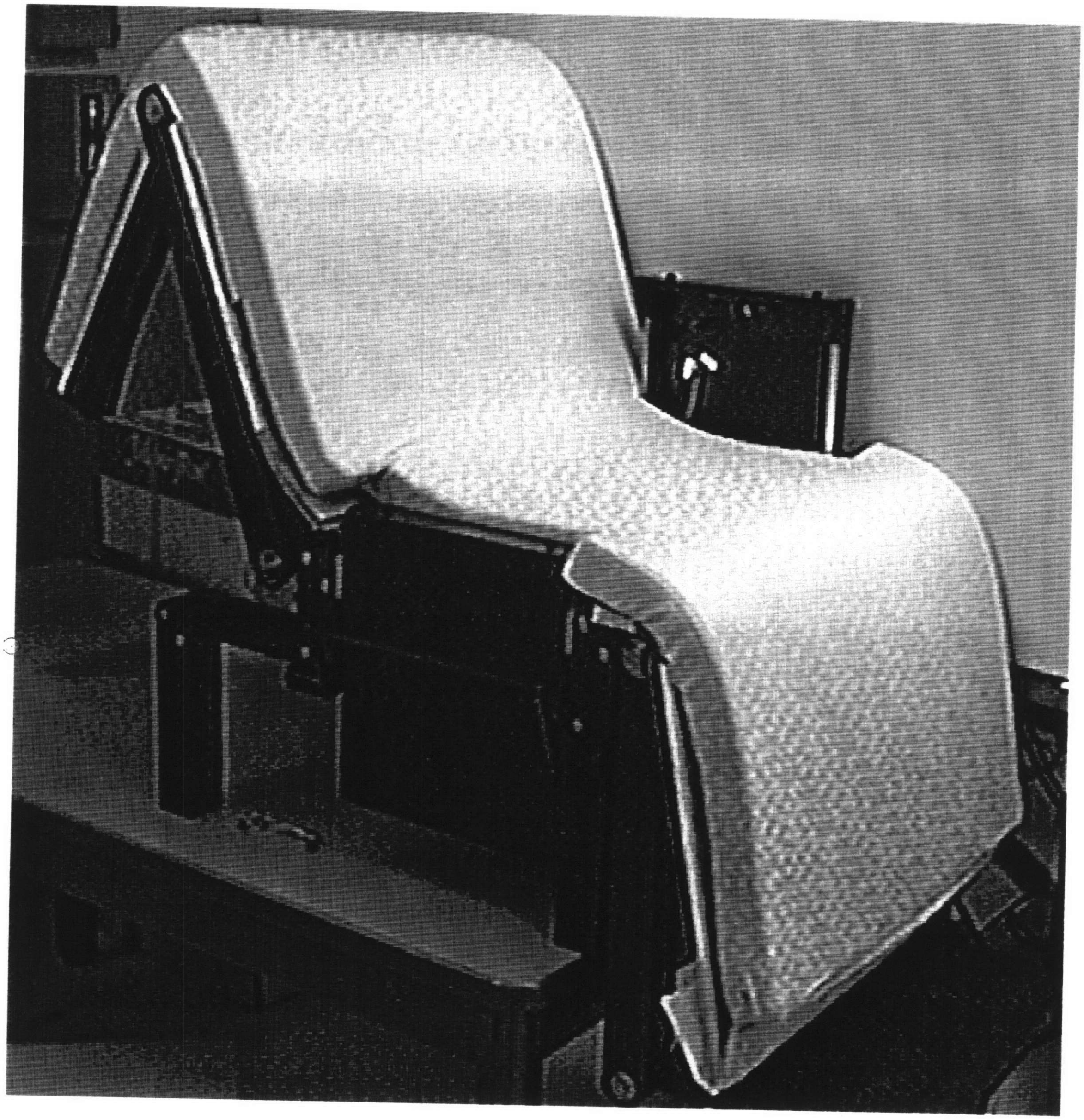


Figure 4.2 1-DOF Bed/Chair in Seated Configuration

Actuation is achieved by DC servomotors through a planetary gearbox and worm gear transmission. Coordination of the the back support leaf with the front support leaf is achieved by a four bar linkage most easily shown in Figure 4.3. Steel belts traveling through the back and neck support leaf frame tubes coordinate the neck and footrests with the rotation of the back and leg support leaves. Figure 4.4 shows a top view of the 1-DOF bed/chair and the steel belts run inside the 2x2 inch tubes that make up the frame rails. These belts are invisible to the patient and provide a transmission mechanism that is completely safe. When the chair moves from a lying to a seated position the footrest rotates 90 degrees relative to the leg support leaf to provide feet support for the patient. This 90 degree rotation is provided by a one-one pulley ratio between the seat frame and the footrest drive shaft. When the chair moves from a lying to a seated position the neck rest which is no longer needed is curled behind the back support leaf by a 180 degree rotation relative to the back support leaf. This rotation is provided by a 2:1 pulley ratio between the seat frame and the neckrest drive shaft.

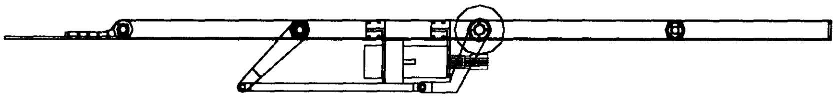


Figure 4.3 CAD Drawing of Side View of the 1-DOF Bed/Chair

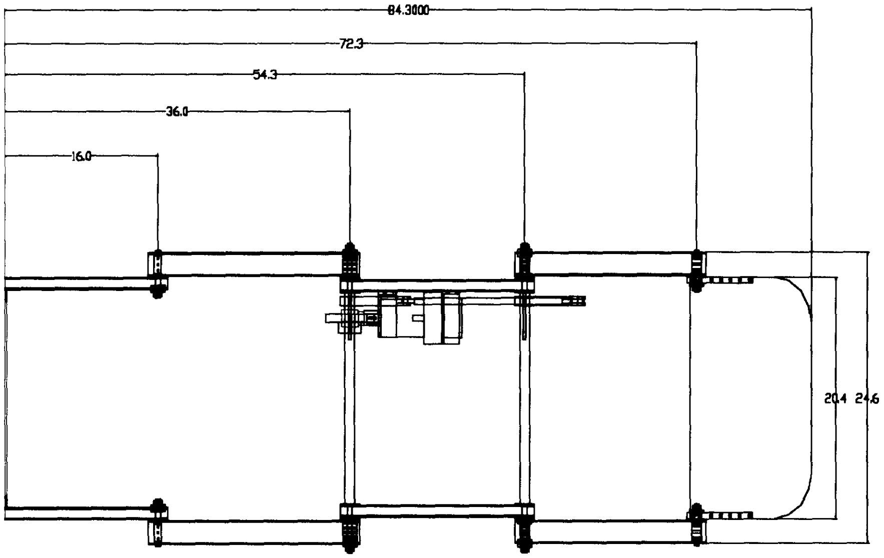


Figure 4.4 CAD Drawing of Top View of the 1-DOF Bed/Chair

The two chairs have been built to explore the different controllable spaces possible with different actuation abilities. For certain applications one degree of freedom may be sufficient, however other objectives may require the increased controllable space of the five degree of freedom bed/chair. Other objectives may be out of reach of both systems and our research should indicate what actuation ability is necessary to match the controllable space spanned by our control objectives. Additional research efforts can be focused on development of new actuator technologies designed specifically to expand our controllable space.

Chapter 5

Interpretive Control of a Human-Centered Manipulator

5.1 Introduction and Related Work

The design of the 5-DOF reconfigurable chair provides a mechanical framework capable of solving a variety of physical assistance needs of the elderly, however questions concerning how to exploit the 5-DOF servoing capabilities of the chair to best meet the needs of elderly patients with limited mobility is a critical issue. Specifically, what range of tasks could conceivably be approached, how to best communicate human intention to the chair, and how to best match the chair's servoing capabilities with human preference. Issues of task definition can be clarified by answering the following questions.

- What is the human's desired motion objective?
- Is the manipulator physically capable of meeting this objective?
- What set of human signals fully describes his/her control desire?
- Can these signals be measured or estimated?
- What closed-loop dynamic behavior of the human-centered manipulator is preferred by the human?

Answering these questions clearly defines the role to be played by the bed/chair system and provides a structure and performance objectives to begin system design for a human-centered manipulator.

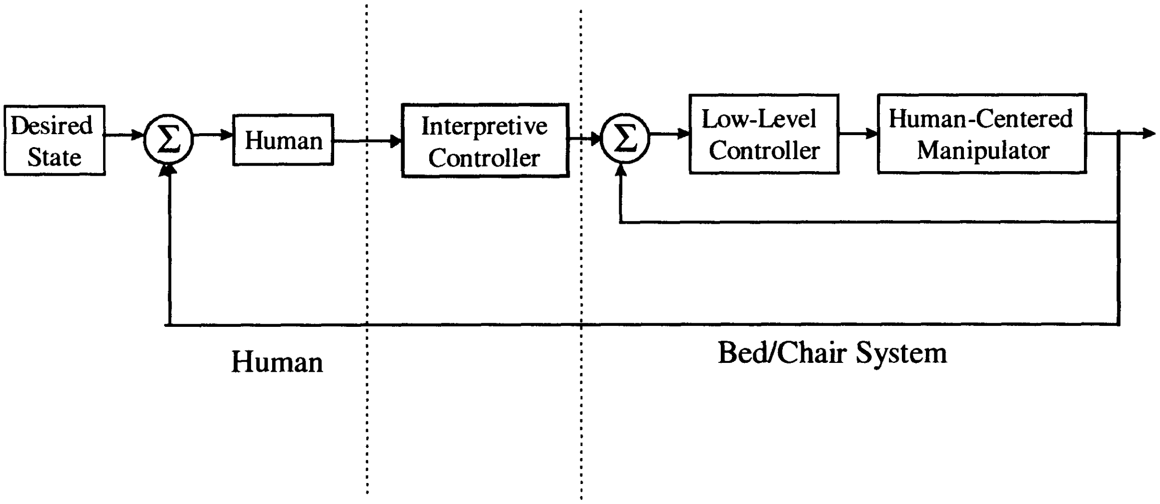


Figure 5.1.1 - Block Diagram of a Human-Centered Manipulator

Figure 5.1.1 illustrates the human and the bed/chair system connected by an interpretive controller. A suitable control system must be synthesized to implicitly extract the human desire for robot position and control the chair to best meet those desires. This machine behavior, not only puts the human in the control loop, but puts the human in charge of the chair in a way that he or she is most comfortable. The interface is implicit, the machine reads and interprets human signals that naturally indicate the human desire. This is contrary to typical fixed human-machine interfaces that are rigidly defined by the machine and must be adopted by the human.

Typical human-in-the-loop systems such as master/slave systems look to control some other object and physical feedback comes from artificially generated stimuli. Additional work that involves human-machine interchange of information and power signals to augment human strength in lifting tasks is presented by [Kazerooni, 1993]. The human extender concept of muscle augmentation is analogous, but does not include the human signals as a portion of the closed loop. In the human extender concept the human signals are external inputs into the closed-loop machine system. The human extender system works in a similar way as our system, but again the object being manipulated is external, not the human him/her self. Current research in the area of control of the chair surface contour has focused on equalizing pressure on the seat of the chair [Brienza, 1996]. Other foci in the rehabilitation robotics field have been in highly specialized areas such as feeding or lifting [Kawamura, 1995], [Khatchadourian, 1994].

A central research issue of this work is the development of the implicit communication scheme, having the chair actively measure physical quantities, and by proper interpretation, decide on and execute the appropriate system response. In this way the human is not responsible for communicating his/her desire in a manner acceptable to the machine, rather the machine is actively searching for human preference based on natural human tendencies that act as indicators of desired changes to his/her environment. In addition to interpretation of human desire the controller must also adapt itself to provide a system response that satisfies appropriately chosen performance indices. The type of control proposed to resolve this situation is the interpretive control of a human-centered manipulator using an admittance controller.

5.2 Formulation of Task Objective and Performance Index

A human-centered manipulator such as the reconfigurable bed/chair is characterized by the fact that it interprets human desire and formulates a control action that directs physical effort upon the human exclusively. The unique feature is that the human defines the control input, consciously or subconsciously, and is physically controlled. This implies that the human is present in the control loop and must be considered. Furthermore, performance indices for the system are centered around the human response because the manipulation of the human is the control objective. The task objective can be clearly defined by answering the questions posed in the introduction.

5.2.1 Problem Statement

A common problem encountered by the elderly is difficulty sitting up in bed. As a matter of fact 80% of the patients in elderly care facilities are there simply because they were no longer able to arise from bed in the morning and successfully move from the bed to a walker or chair. Typically human assistance is needed to lift and support the elderly in a seated position for feeding or in preparation to move off of the bed. The multi-DOF bed/chair system possesses the actuation ability to move the human from a lying to seated position by servoing of the backleaf, relieving the infirmed patient of the daunting task of pulling oneself from a lying position. See Figure 5.2.1.1.

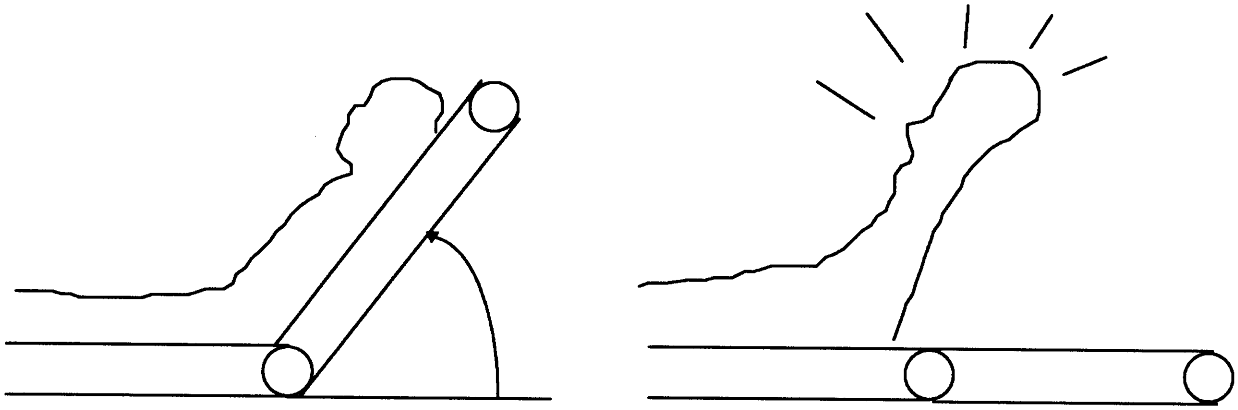


Figure 5.2.1.1 - Powered Chair Backleaf for Physical Assistance

The task of the chair is to sense abdominal muscle exertion, correctly interpret this exertion as a desire to change position, and move the chair in the appropriate direction to relieve the exertion. In this way the chair interprets the human desire and moves to achieve this goal. We want to augment the human effort required to reconfigure from a seated to lying position by controlling the motion of the backleaf of the chair to reduce to zero the abdominal muscle exertion of the human at any particular time. The chair amplifying the humans signal can be considered muscle augmentation.

5.2.2 Human Signal Identification and Measurement

Now that we have established a physical assistance need and verified the bed/chair's capability to fill that need we must identify signals generated by the human that indicate a desire to change the position of the backleaf of the chair. A logical way that a human could communicate how he or she would prefer to be seated would be to exert abdominal muscle force and back muscle force in tandem in an attempt to alter chair position and move toward a more desirable state. Figure 5.2.2.1 illustrates the human abdominal and back muscles working as a tandem drive unit. These muscle exertions are the physical signals the human outputs to indicate a desire to move his/her seat position.

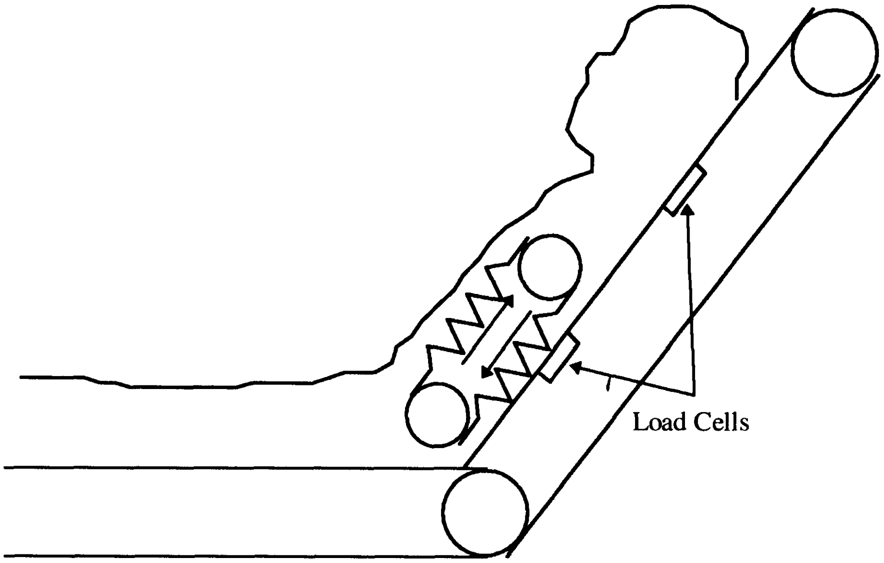


Figure 5.2.2.1 - Human Muscles as Tandem Drive Unit and Load Cells to Measure Contact Force

The next question concerns whether the human muscle signals can be measured or estimated. The evaluation of human preference as determined by the level of muscle exertion can be approached in many ways. Psycho-physical queries can be utilized to get an estimate of human exertion. The validity of these results is questionable and use of this method in the home setting is impractical. Direct physical measurement of muscle exertion may be possible, but again, probing the human, possibly in vitro is totally impractical and defeats the ideal of a comfortable, non-invasive human-machine relationship. Instead, if simple, non-invasive physical measurements can be made and the signals processed to estimate the level of human exertion, the machine will have the knowledge necessary to adapt itself to human preference. The contact surface between the human back and the backleaf of the chair is a place where force data can be obtained that contains the human muscle exertion information we seek. In this research load cells were utilized to measure the interaction force between the chair surface and the human. Figure 5.2.2.1 illustrates the use of load cells to measure the contact force between the human body and the backleaf. This type of instrumentation was utilized to be non-invasive, so the patient will be unaffected by the measurement process.

5.2.3 Specification of Performance Index

Our challenge is to establish a control structure that successfully realizes physical augmentation tuned to each individual's preference. This preference must be quantitatively defined. The human is most comfortable in this scenario when he or she has to exert a minimum amount of control (muscle effort) to make the chair follow his/her desired position. We define this preference as a minimum energy effort on the part of the human. If we define F_h as the muscle force exerted by the human we would like the following performance index to be minimized by our control strategy.

$$J = \int_0^\infty |F_h|^2 dt \tag{5-1}$$

5.3 Specification of Interpretive Controller Architecture

Now that the functionality and performance index for the human-centered manipulator have been clearly defined, a specific architecture for the interpretive controller must be established. It would be desirable to implement a control strategy that requires a minimum amount of muscle exertion to induce chair motion, but allows for spurious changes in muscle force to be filtered by the chair system. Specifically the chair should sense the human's desire to change chair position by reading the muscle signals exerted by the human. The chair should move in a direction that relieves these muscle forces until the human stops exerting which indicates that the desired position has been reached. Given this design criteria, admittance control with an interpretive filter is a logical structure for the interpretive controller because it allows a force to be generated while absorbing spurious force inputs. Figure 5.3.1 illustrates a block diagram of the controller.

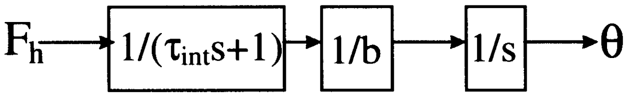


Figure 5.3.1 - Controller Transfer Function

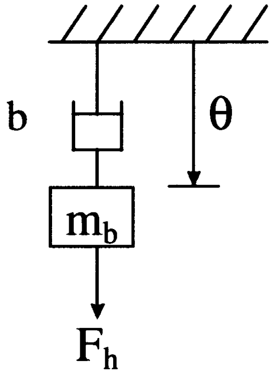


Figure 5.3.2 - Mechanical Analog

A mechanical analog to the proposed controller is shown in Figure 5.3.2. The controller acts like a damper that is characterized by the parameter b. As long as there is a human force generated, the reference chair position, theta, moves in the direction of the force. The rate at which the chair position changes for a given force input is governed by the value of the parameter b. The low-pass filter characterized by parameter, τ_{int}, acts like a mass element where the force is applied and effectively damps out high frequency oscillations of the human muscle force.

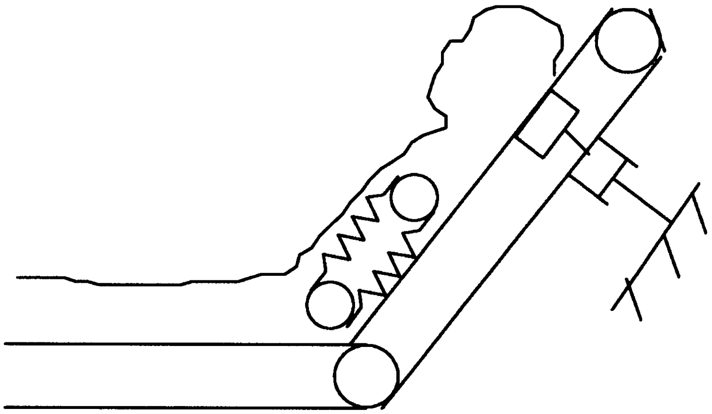


Figure 5.3.3 - Schematic of Controller in System

So effectively, in Figure 5.3.3, the human must exert muscle force for some dedicated period of time before the reference position will begin to change.

5.4 Model Formulation and Assumptions

Figure 5.4.1 illustrates a simplified model of the human-centered manipulator system. The human is modeled as a link element of mass m_h resting on the chair/bed structure represented as a separate link of mass m_r. The human muscle exerted on the chair/bed structure is modeled as the externally applied force F_h. The mass centroid of each link element and the applied muscle force act at specific distances from the rotational joint of the backleaf. Each of these lengths are specified. The chair position theta is specified. Gear reduction and motor constants are included. Of course gravity which plays a strong role in this system is modeled. A list of parameters, their definitions, and estimates of actual values are given:

Parameter	Estimate	Description
m_h	50lb=22.68kg	Mass of the human
m_r	10lb=4.54kg	Mass of the chair link

F_h		Muscle force exerted by human
θ		Chair position
l_h	.75m	Moment arm of human mass
l_r	.75m	Moment arm of backleaf mass
l_m	.75m	Moment arm of F_h
G_r	980:1	Gear transmission reduction
V_0		Voltage applied to motor
K_1	.046Nm/Amp	Motor torque constant
K_2	.084 Volts/rad/sec	Back emf constant
J_m	.00005865Nms^2	Motor inertia
R	.660 ohms	Motor armature resistance

The resulting equation of motion for this system is

$$G_r^2 J_m \ddot{\theta} = -\frac{K_1 K_2 G_r^2}{R}\dot{\theta} + \frac{G_t K_1}{R} V_0 + m_h g l_h \sin\theta + m_r g l_r \sin\theta + F_h l_m + \tau_{sf} \qquad (5\text{-}2)$$

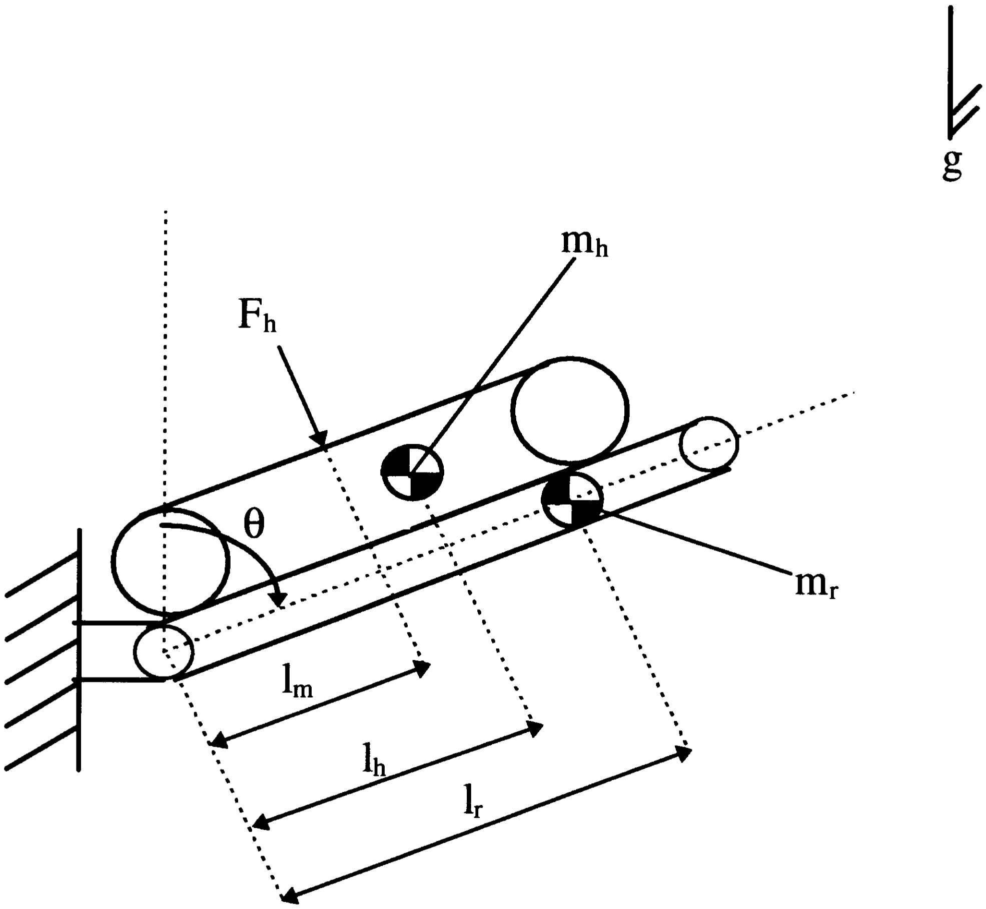


Figure 5.4.1 - Schematic Model of Bed/Chair System

The model has several key assumptions. Due to the slow, quasi-static nature of the motion of the mechanism, dynamic effects of the robot/human system have been ignored, although inertia affects of the motor have been included due to the extremely high gear reduction utilized in this system. Also due to the quasi-static nature of the motion, link flexibility of the chair/bed structure and the human/chair interaction have been ignored and assumed to be rigidly connected. Static friction which is significant in this system with high gear reduction has been included in the equation of motion. An additional assumption has been made that the human mass centroid is located with the same theta parameter as the robot structure. This movement of angle reference point from the human hip joint to the bed/chair backleaf rotational joint simplifies the system equations and since mass properties must be estimated anyway this change of reference will not affect the time-varying parameter estimation algorithm.

5.5 Gravity Load Estimation and Compensation

The system equations of motion are nonlinear due to the presence of gravity load as a function of the sine of theta. To begin the detailed design of a controller we would like to linearize these equations by compensating for gravity to cancel its effects in the system equations leaving behind linearized equations of motion that can be dynamically compensated by traditional linear control designs such as a PD controller. Gravity load affects the control of the chair/bed system in another way. The gravity load is a portion of the contact measurement made between the human body and the manipulator. Since we are interested in the human muscle load in this contact measurement we would like to subtract out the contribution of gravity load in this measurement. Estimation of the gravity load is difficult because modeling can give us the functional relationship between the gravity load and chair position, but because our mass parameters and center of mass locations cannot be determined accurately and are time-varying we cannot get exact values for compensation. To solve this problem I employ a recursive least squares parameter estimation algorithm with a forgetting factor to properly estimate and track the time-varying gravity load. These estimates are used to design a gravity compensator for the human muscle force measurement and a gravity and friction compensator for the servo controller illustrated in Figure 5.5.1.

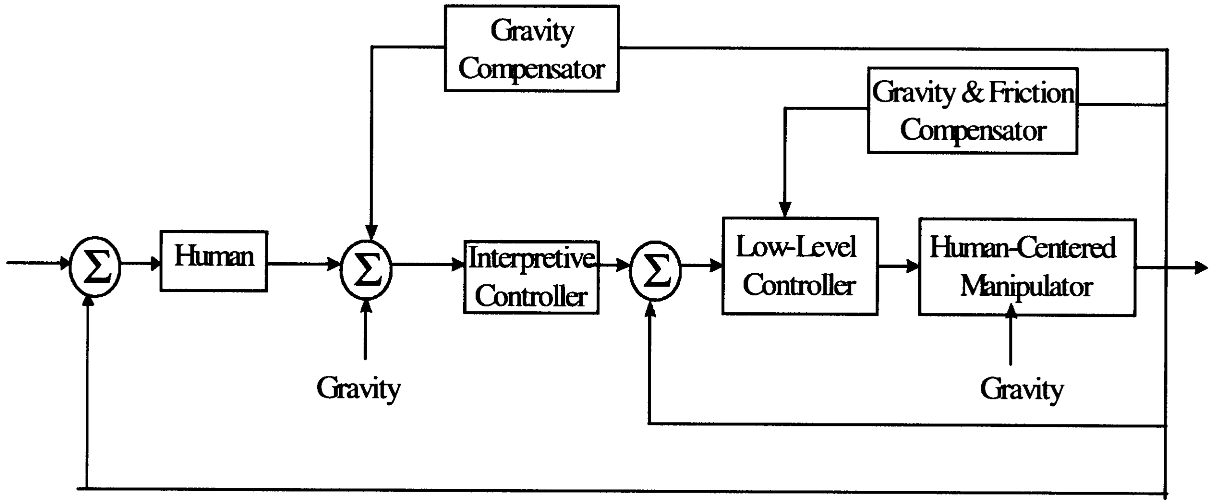


Figure 5.5.1 - Block Diagram of Bed/Chair System

The gravity load is nonlinear and affects both the high and low level feedback loops as shown in Figure 5.5.1. By gravity compensation we estimate the gravity load and introduce a static signal that negates its effect leaving a linearized dynamic system in the case of the machine level loop and a pure measurement of muscle exertion at the load cells.

5.5.1 Gravity Compensation of Contact Force Measurement

In our system the gravity load is a function of chair position, human mass properties and human position on the chair. From our model;

$$G(\theta, m_h, l_h) \qquad (5\text{-}3)$$

In the case of contact force measurements the gravity load enters as follows:

$$G(\theta, m_h, l_h) = m_h g \sin\theta \qquad (5\text{-}4)$$

First we must design the gravity compensation estimator for the contact force measurement. Referring to the system model it is apparent that

$$F_{contact} = F_h + m_h g \sin\theta \tag{5-5}$$

This expression contains the measurable quantities $F_{contact}$ and θ to be used in our estimation algorithm. Since the human position on the chair is time-varying and the exact mass properties of the human are difficult to measure we will employ the recursive least squares technique for parameter estimation to accurately estimate the unknown mass parameter. In addition we will utilize a forgetting factor to discard old data that is no longer relevant as the human changes position on the chair. A fundamental assumption needed to utilize this technique is that over sufficiently long time periods the unknown F_h time averages to zero. This assumption can be safely made when it is considered that the human cannot exert significant muscle forces for a long period of time without tiring and eventually exerting no muscle force. With this assumption made

$$\mathbf{F}_{contact} = m_h g \sin\Theta \tag{5-6}$$

We can measure $F_{contact}$ and θ. In addition g is known and the parameter left to estimate is m_h. We can rewrite the expression in the form

$$(g \sin\Theta) m_h = \mathbf{F}_{contact} \tag{5-7}$$

We want to estimate a value for m_h that minimizes the squared error function given as

$$e^2 = \left| F_{contact} - m_h (g \sin\theta) \right|^2 \tag{5-8}$$

By differentiating this function with respect to the parameter m_h and setting this result equal to zero we obtain an expression for the estimate of m_h given by

$$m_h^{(n)} = \frac{\mathbf{F}_{contact}{}^{T} g \sin\Theta + F_{contact}{}^{(n+1)} g \sin\theta^{(n+1)}}{\left(g \sin\Theta\right)^{T} \left(g \sin\Theta\right) + (g \sin\theta^{n+1})^2} \tag{5-9}$$

Considering that the parameter we are estimating is time varying it is useful to introduce a forgetting factor that decreases the weight of influence of older data that is no longer relevant to the estimation of the parameter. This forgetting factor allows us to better track the time varying parameter. With this forgetting factor λ, in place the expression for the estimate of m_h becomes

$$m_h^{(n)} = \frac{\lambda \mathbf{F}_{contact}^{T} g \sin\Theta + F_{contact}^{(n+1)} g \sin\theta^{(n+1)}}{\lambda \left(g \sin\Theta\right)^{T} \left(g \sin\Theta\right) + (g \sin\theta^{n+1})^{2}} \tag{5-10}$$

5.5.2 Forgetting Factor Design Criteria

With the introduction of the forgetting factor we have introduced a new design parameter. When first looking at the situation it would make sense to choose the forgetting factor so that all data that corresponds to the time scale of human movement on the chair is included. This human movement is most likely to occur when the chair undergoes reconfiguration and the body is shifted on the chair. With this thought we would choose the forgetting factor along the time scale of chair reconfiguration. However, we must remember that the use of recursive least squares estimation for this problem is predicated on the fact that over long enough periods of time the human muscle force is time-averaged to zero. Therefore it is of utmost importance that the forgetting factor be chosen to include enough data that this assumption holds true. So the limiting criteria for choosing the forgetting factor parameter is chosen to be on the time scale of significant, continuous human muscle exertion.

5.5.3 Gravity and Friction Compensation in Servo Loop

With the estimation process completed to properly compensate for gravity load in the contact force measurement we must consider the estimation of parameters necessary to compensate for gravity and static friction in the servo loop. At steady state the equation of motion that governs the human/robot system becomes

$$0 = \frac{G_r K_1}{R} V_0 + (m_h l_h + m_r l_r) g \sin\theta + F_h l_m + \tau_{sf} \tag{5-11}$$

Solving for the necessary gravity compensation voltage to be applied to the motor you obtain

$$\bar{V}_o = -\frac{R}{G_r K_1}\left[(m_h l_h + m_r l_r) g \sin\theta + F_h l_m + \tau_{sf}\right] \tag{5-12}$$

This equation has several unknown parameters so we must estimate these quantities to perform this calculation. Let us return to the system equations of motion. This time we will replace the acceleration with a general torque term.

$$\tau = -\frac{K_1 K_2 G_r^2}{R}\dot{\theta} + \frac{G_r K_1}{R} V_0 + m_h g l_h \sin\theta + m_r g l_r \sin\theta + F_h l_m + \tau_{sf} \tag{5-13}$$

We do this because this torque can be measured indirectly by measuring current and using the motor torque constant to obtain this torque. Current drawn by the motor for a given applied voltage can be converted to this torque using the relation

$$\tau = K_1 i \tag{5-14}$$

This current can be measured and used to derive τ to be used in the estimation process. Since there are several unknown parameters in the equation governing the gravity compensator for the servo loop we will again employ least squares estimation with the forgetting factor to properly estimate unknown parameters needed to calculate the gravity and friction compensator. Under the assumption that over long enough periods of time muscle force, control voltage, and joint angular velocity time averages to zero we are left with

$$K_1 i = (m_h l_h + m_r l_r) g \sin\theta + \tau_{sf} \tag{5-15}$$

The parameters to be estimated are τ_{sf} and the lumped parameter $m_h^* = m_h l_h$. Theta and current are measured and all other quantities are known. The squared error function is given by

$$e^2 = \left\| (K_1 i - m_r l_r \sin\theta) - \begin{bmatrix} 1 & g\sin\theta \end{bmatrix} \begin{bmatrix} \tau_{sf} \\ m_h^* \end{bmatrix} \right\|^2 \tag{5-16}$$

The estimation algorithm that minimizes this error including the forgetting factor that is chosen using the same criteria explained before is

$$\begin{bmatrix} \tau_{sf} \\ m_h^* \end{bmatrix} = \left(\lambda \sum_k \mathbf{Y}^{\mathbf{k}^T} \mathbf{Y}^k + \mathbf{Y}^{(n+1)^T} \mathbf{Y}^{(n+1)} \right)^{-1} \left(\lambda \sum_k \mathbf{Y}^{k^T} \tau^k + \mathbf{Y}^{(n+1)^T} \tau^{(n+1)} \right) \tag{5-17}$$

Given that

$$\mathbf{Y} = \begin{bmatrix} 1 & g\sin\theta \end{bmatrix} \tag{5-18}$$

and

$$\tau = K_1 i - m_r l_r \sin\theta \tag{5-19}$$

Since we are trying to estimate two parameters it is necessary to provide persistent excitation. It is assumed that during the normal training session this assumption holds true.

5.5.4 Resulting Linearized System

Assuming that estimator dynamics are much faster than the system bandwidth we can rewrite the system block diagram with gravity and frictional effects removed and deal with the resulting linearized system shown in Figure 5.5.4.1.

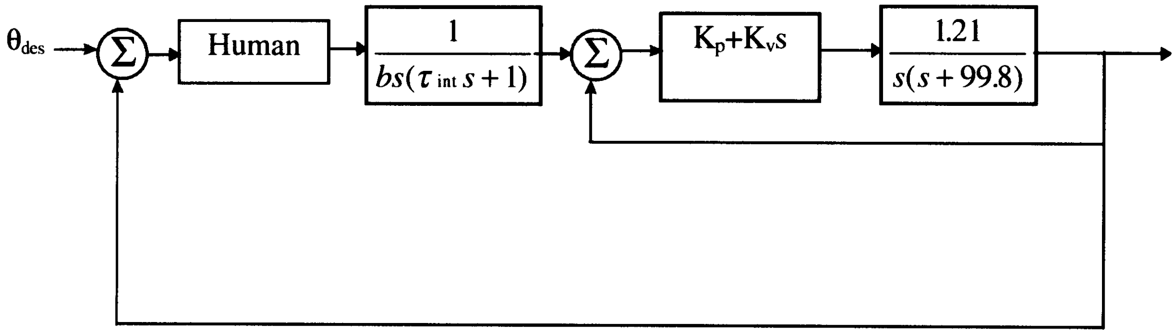


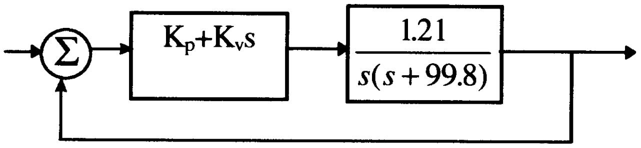
Figure 5.5.4.1 - Resulting Linearized Bed/Chair System

5.6 Human Model Assumption and System Stability Criteria

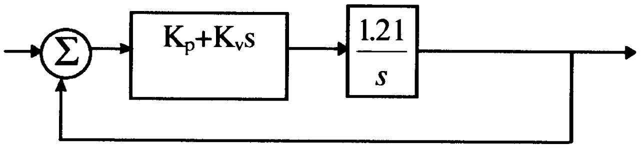
With gravity compensation in place we can begin to make an evaluation of the resulting closed loop including the human. To begin the analysis we must reduce the servo loop to isolate the human-machine loop. A model for the human must be developed and stability criteria for this human-machine system must be derived.

5.6.1 Reduction of Machine Servo Loop

First let us focus on the machine servo loop.



By ignoring high order dynamics represented by the term 1/(s+99.8) we are left with the following.



Calculating the closed loop transfer function for this system yields the following result.

$$\frac{1.21K_v s + 1.21K_p}{(1.21K_v + 1)s + 1.21K_p} \tag{5-20}$$

Clearly if control gain K$_v$ is chosen such that

$$1.21K_v >> 1 \tag{5-21}$$

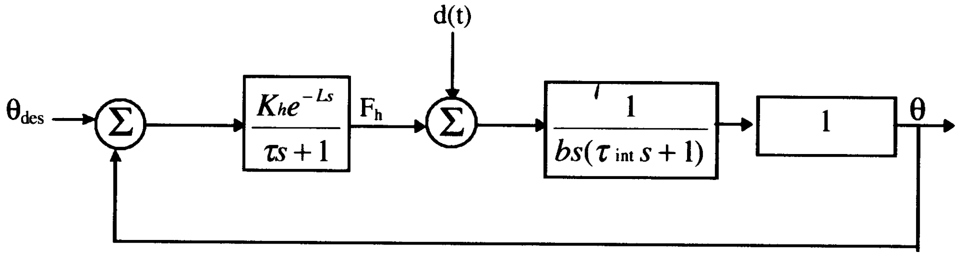
by introducing reasonably high servo gains the closed loop servo response can be approximated as unity.

5.6.2 Human Model Formulation and Assumptions

In addition the human response function must be estimated. It is assumed that the human response function is of the form

$$\frac{F_h(s)}{e(s)} = K_h \frac{e^{-Ls}}{\tau s + 1} \tag{5-22}$$

This response function includes a first order response to characterize muscle response characteristics and a time delay element to account for time needed for human perceptual processes to occur. [Sheridan and Ferrell, 1974] suggests that reaction time-delay is approximately 0.15 seconds. This includes neural synaptic delays, nerve conduction time, and processing time. Neuromuscular lag is characterized by a time constant of approximately 0.2 seconds. With this model in place and with the results of closing the machine loop the resulting block diagram is illustrated.



It is from this model that we will begin our control design synthesis.

5.6.3 Derivation of Closed-Loop Stability Criteria

The first issue to address is closed loop stability. This system is complicated by the presence of a transport lag in the human model. This lag introduces serious stability consequences that must be addressed. By series expansion we can obtain a polynomial expression for the transport lag term

$$e^{-Ls} = \frac{1 - \frac{Ls}{2} + \frac{(Ls)^2}{8} - \frac{(Ls)^3}{48} + \cdots\cdots}{1 + \frac{Ls}{2} + \frac{(Ls)^2}{8} + \frac{(Ls)^3}{48} + \cdots\cdots} \qquad (5\text{-}23)$$

To good approximation this expression can be simplified to

$$e^{-Ls} = \frac{2 - Ls}{2 + Ls} \qquad (5\text{-}24)$$

provided that the following criteria is met. [Ogata, 1990]

$$0 \le \omega \le \frac{1}{2L} \qquad (5\text{-}25)$$

In our case we should specify the bandwidth of our system to be below 1/2L for this approximation to hold.

With this assumption in place we can replace the exact exponential expression for transport lag with the approximate polynomial expression for our stability analysis.

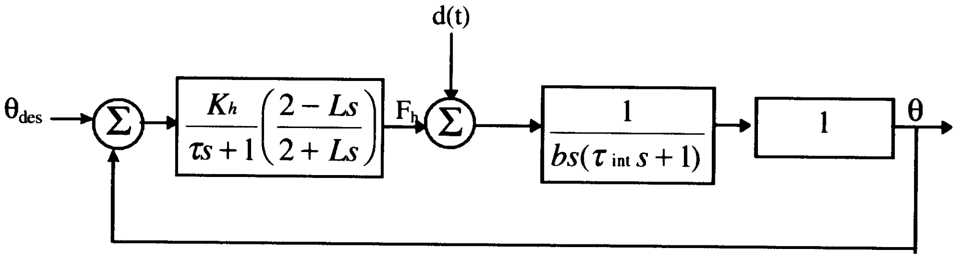


Figure 5.6.3.1 - Simplified System Block Diagram

Open loop stability is guaranteed for this system as all open loop poles lie in the left half of the phase plane, knowing that all time constants are positive and assuming a positive choice for parameter τ_{int}. However closed loop stability for this system is not guaranteed and is probably severely bounded due to the non-minimum phase behavior induced by the transport lag. This lag manifests itself as a linear increase in phase with frequency and for this reason system bandwidth will be limited. To determine an analytical bound for system gain before the closed loop system goes unstable we analyze the expression

$$(1\text{- Loop Transmission})=0 \tag{5-26}$$

which when plotted is the root-locus of the closed-loop system. Knowing that at least one of the closed loop poles will migrate toward the non-minimum phase zero in the right half of the phase plane, we would like to find the value of gain set by 1/b where the closed loop poles cross the imaginary axis into the right half plane, thus setting a hard stability criteria for this system. This occurs when the real part of this expression holds true.

$$1+\left(\frac{1}{b}\right)\left[\frac{K_h}{\tau s+1}\left(\frac{2-Ls}{2+Ls}\right)\frac{1}{s(\tau_{int}s+1)}\right]=0 \tag{5-27}$$

By substituting s=jω into this expression, separating real and imaginary parts, and setting the imaginary parts to zero we realize an analytic expression that sets the boundary for system gain before instability is reached.

$$b \geq \left[\left(\frac{K_h}{1+(\tau\omega)^2}\right)\left(\frac{4-(L\omega)^2}{4+(L\omega)^2}\right)\left(\frac{\tau_{int}}{(\tau_{int}\omega)^2+1}\right)\right] \tag{5-28}$$

The parameter b is our choice and acts to set the system gain. This expression sets the lower bound on b to ensure stability. We should choose b greater than or equal to this value so system gain is lower than or equal to the boundary of stability since the inverse of b is the system gain when examining the open loop transfer function.

5.7 Design Methodology for Interpretive Controller

Now that the hard line stability criteria has been analytically determined for our human-centered system we would like to complete our system design. We have two parameters to choose. The first is parameter, τ_{int}, which acts as our human interpreter and the second is parameter, b, which determines the loop gain. In addition we must determine approximate values for parameters of the human transfer function experimentally and off-line. The procedure is to determine human parameters experimentally, set parameter, τ_{int}, to set system bandwidth subject to our series expansion truncation assumption and experimental results analyzed off-line. Then using frequency analysis design techniques we can choose b to ensure proper gain and phase margin while maximizing system bandwidth.

5.7.1 Evaluation of Human Transfer Function Parameters

The evaluation of the human response function is obtained by having the human sit comfortably in the chair and asking him or her to relax and try to maintain zero force on the backleaf of the chair at all times. Then we introduce a step change in chair position and monitor the human reaction to this step change in position. Based on this response we can evaluate whether our assumed structure indeed fits reality and if so, we can determine the parameters of this model from the response characteristics. From these results we can infer the time constant for human muscle reaction, τ, the static human gain, K_h, and the estimated perceptual transport lag, L.

5.7.2 Determining Interpretive Filter Parameter

The low-pass filter defined by $1/(\tau_{int}s+1)$ has a special function in this system. This filter structure was chosen to set the bandwidth for control action by interpreting human muscle signals as either a genuine desire to move or simply spurious signals generated by random fluctuations of abdominal muscle or movements of the human on the chair. Another function of this filter is to reject disturbances introduced into the system at the sensor measurements represented in Figure 5.6.3.1 by d(t). These two performance objectives translate graphically to specific dynamic performance requirements in the frequency domain as regions that should not be crossed by the frequency response plot. This is illustrated by an example Bode plot shown in Figure 5.7.2.1. Spurious human movements on the chair must be rejected because they are interpreted as unintentional force perturbations that do not accurately reflect the human's desire. The placement of this region on the frequency response plot is determined by the cut-off frequency of our interpretive filter. The low frequency range of the Bode plot shows a region we would like to avoid so that the system has high stiffness and effective response at low frequencies when the human desires to move and is exerting effort. In addition stability concerns play an important role the forbidden region of the phase plot. It is here that we would like to specify a safe phase margin that can absorb errors in modeling and parameter variation.

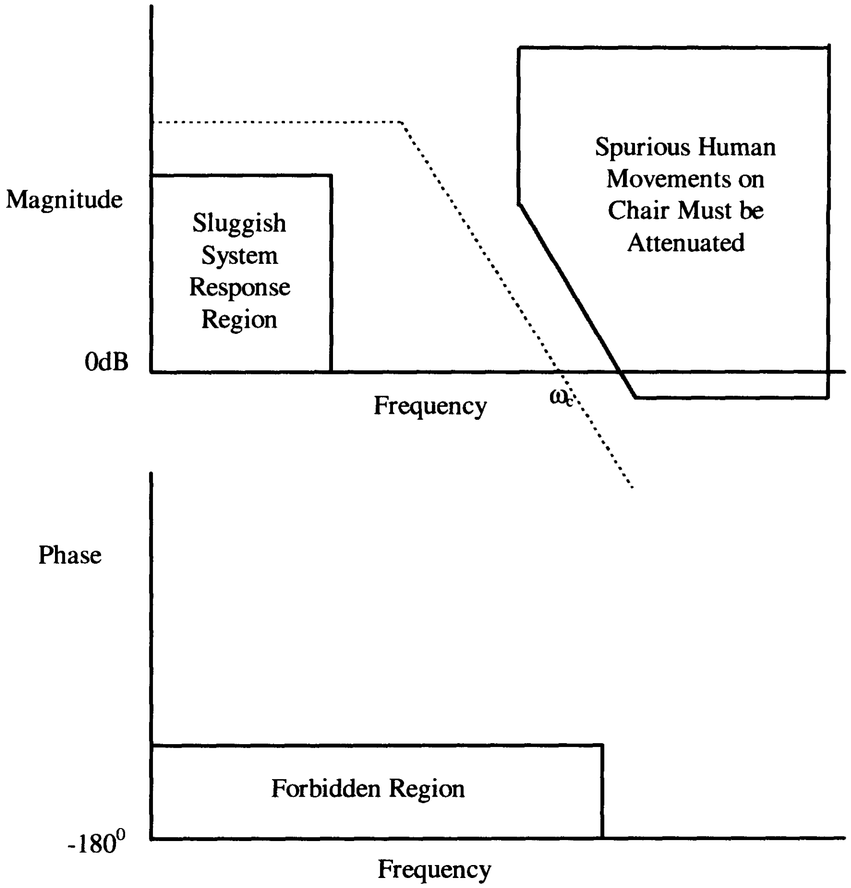


Figure 5.7.2.1 - Sample Bode Plot Illustrating Design Specifications

To obtain a value for parameter τ_{int}, experiments must be run where the human is requested to relax and get comfortable on the chair. Contact force measurement data should be taken over a certain period of time and the frequency spectrum of this data calculated and evaluated. A cut-off frequency should be chosen to separate high frequency fluctuations of human motion induced by sensor noise and random movements on the chair from low frequency components that indicate the human is interested in changing the chair position. This separation is the cut-off frequency for the interpretive filter.

5.7.3 Criteria for Specifying Loop Gain

By our choice of parameter b we establish system gain. This gain should be chosen subject to several constraints. Our system should have at least 60 degrees of phase margin which is illustrated in the phase plot in Figure 5.7.2.1. This is a conservative figure, but is warranted for two reasons. First, it is evident that the human response function exhibits some time delay associated with human perception and phase margin is a measure of the controllers ability to maintain stability in the face of unmodeled time delay. Second, we are dealing with a human-machine system and instability can have disastrous consequences and additional phase margin beyond normal machine designs is desirable. This design also should have approximately 12dB of gain margin which is a measure of the systems ability to maintain stability in the face of unmodeled or changing system gain. This large gain margin is warranted because the human transfer function as discussed earlier is time-varying and we would like to ensure stability even in the face of changing human dynamics.

We can also evaluate the effectiveness of our interpretive filter by evaluating its ability to reject disturbances introduced by d(t). The transfer function from disturbance to output is

$$\frac{\theta(s)}{d(s)} = \frac{(\tau s + 1)(2 + Ls)}{bs(\tau_{\text{int}} s + 1)(\tau s + 1)(2 + Ls) + K_h(2 - Ls)} \tag{5-29}$$

The frequency response plot of this function illustrates its ability to reject high frequency disturbances in the form of sensor noise and human movements on the chair.

5.7.4 Design Example

The experimental apparatus used to obtain human response function parameters by the procedure detailed previously is shown in Figure 5.7.4.1. Figure 5.7.4.2 shows the load cells used to obtain the contact force measurements. Sample parameters will be utilized to run through the design process in simulation to illustrate the use of the design criteria and principles described in the previous sections.

Figure 5.7.4.1 - Experimental 5-DOF Reconfigurable Bed/Chair

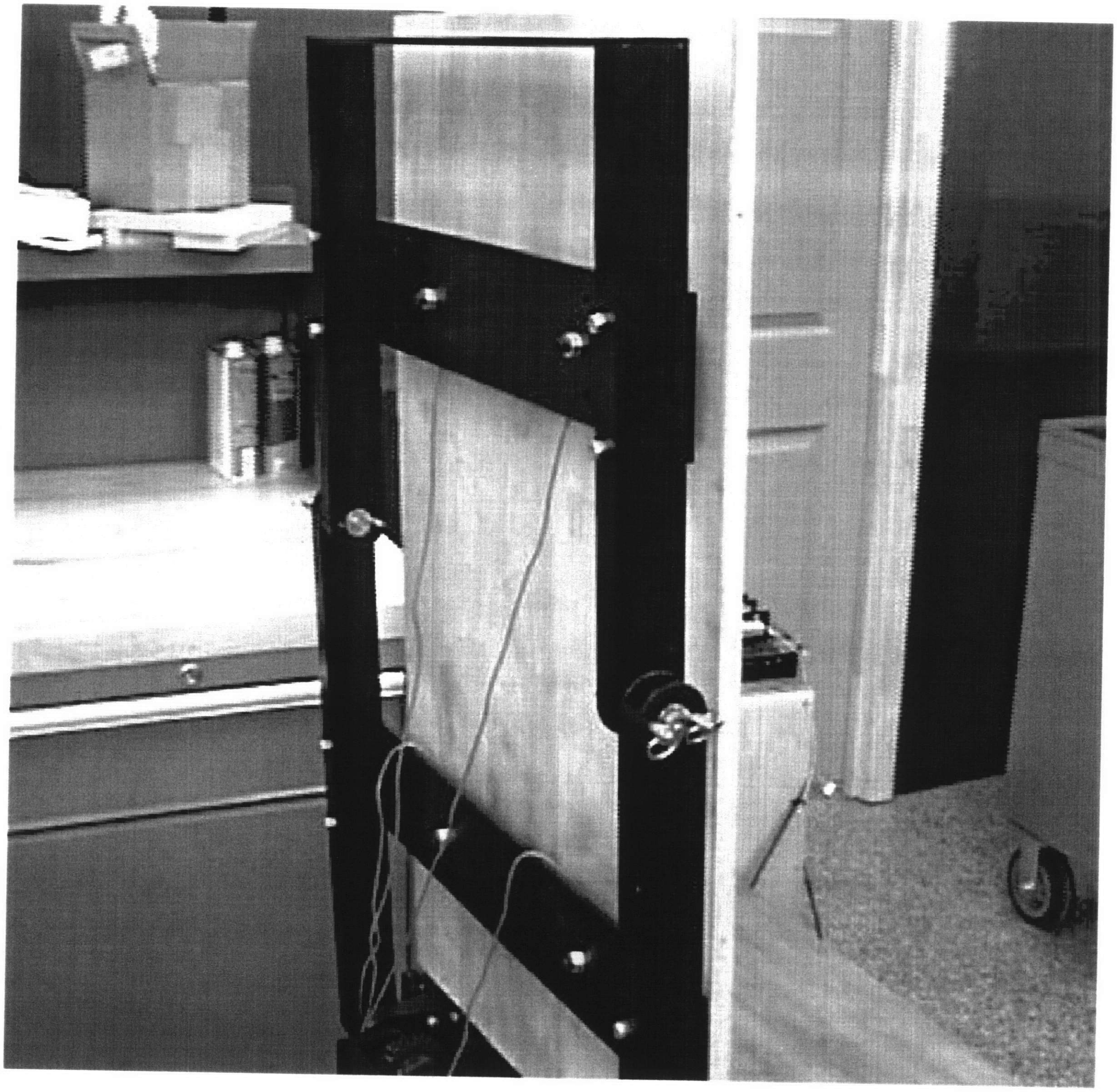


Figure 5.7.4.2 - Instrumented Backleaf of Bed/Chair

Reasonable values for human response function parameters were chosen in accordance with values quoted by [Sheridan and Ferrell, 1974]. The human time delay, L, was chosen to be .15sec. The muscle response time constant, τ, was chosen to be .2sec. The human gain was chosen to be 5. The interpreter cut-off frequency was chosen to attenuate signals above .5Hz. This value was chosen roughly to show that the human will oscillate about the chair on the order of 1Hz and we would like to remove these spurious signals. With these values in place the frequency response of the system was calculated and the gain adjusted to provide the specified gain and phase margins desired for this human-centered system. The results are shown in Figure 5.7.4.3. For this response the parameter b was chosen to be 16.7.

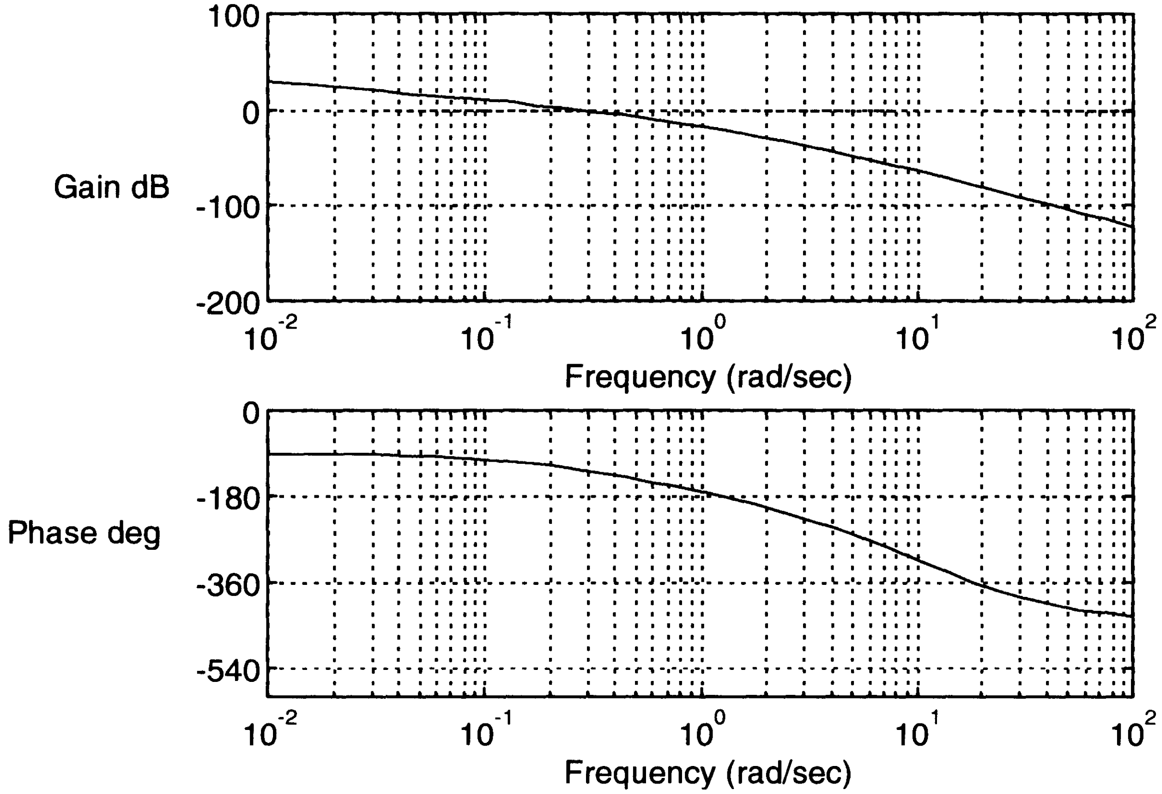


Figure 5.7.4.3 - Simulated Frequency Response Plots

Evaluation of these plots shows a low system bandwidth that is specified by the simple first order interpretive filter. This establishes a baseline for improved interpretation schemes that can still do an adequate job of meeting the human desire for position, but in a more responsive manner.

It is important to recognize that the human model is not only uncertain, but changes with time. The human has control over the nature of his/her response and depending on internal and external stimuli this response function will change. Machine performance, the human level of alertness and energy level at that time, and the human's comfort level with the machine can all affect the human response function. The control design offered in this section is fixed and offers a wide stability margin and high level of robustness and sets limits on how high control gains can be utilized, however recognizing that the human response function will change over time it would be desirable in the future to introduce an on-line tuning method to tune controller parameters to optimize performance under these time-varying conditions.

Chapter 6
Conclusions and Future Work

6.1 Solution of Elderly Transfer Problem by Design

A reconfigurable bed/chair system has been developed at MIT for the Total Home Automation and Health Care/Elder Care Consortium. The immediate application for this mechanical system is the elimination of the difficult bed/chair transfer for the elderly.

6.2 Sensor Interpretation and Control Design to Adapt to Human Preference

As research goals we have implicitly augmented a human's declining ability to perform a task by physical assistance. The specific task that we focused on is the movement from a sitting to a lying position and vice-versa. This work details the design of the controller that exhibits this behavior and the tuning of the controller parameters to satisfy first, stability criteria, then meet performance conditions that make the human as comfortable as possible. An additional design job is choosing appropriate instrumentation to measure muscle exertion and to properly interpret these signals as specific human intentions. The interpretation scheme must be integrated with the controller structure to produce a seamless flow from signal measurement to control action that minimizes our human control energy cost function that is the performance index for this system. Thus another unique feature of this work is the utilization of adaptive techniques to minimize human effort in the form of muscle exertion in the closed loop response of the human-centered manipulator.

6.3 Future Work

6.3.1 On-line Tuning of Controller Parameters

Assuming that estimator dynamics are much faster than the system bandwidth we can rewrite the system block diagram with gravity and frictional effects removed and deal with the resulting linearized system shown in Figure 6.3.1.1. This simplification allows us to focus on the design of the adaptive control law for the human-centered manipulator with a focus on the relationship between the adaptation of the interpretive controller and the human while de-emphasizing the details of the machine execution, however later we should revisit the full dynamics of the system including the estimators to ensure system stability and verify the assumption.

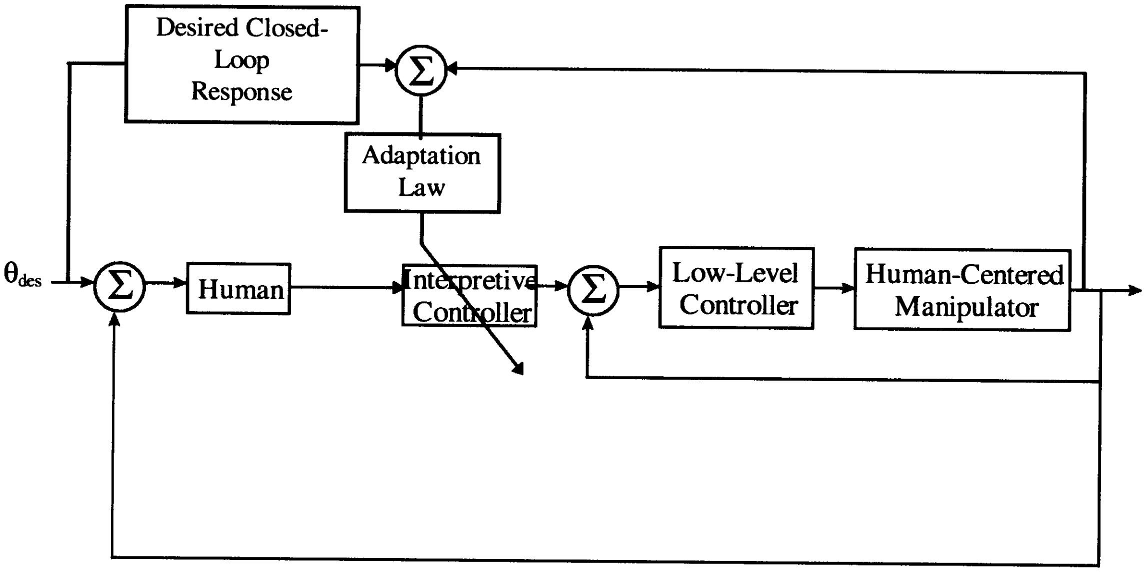


Figure 6.3.1.1 - MRAC Applied to Human-Centered Manipulator

Figure 6.3.1.1 illustrates a generic Model Reference Adaptive Control block diagram. This system compares a predetermined desired closed loop response transfer function with the real response and through an adaptation law, modifies controller parameters to minimize the error between desired and real responses. With the controller structure and gravity compensation in place it is necessary to develop an adaptation law to modify controller parameters online to minimize the human control effort which is our desired performance index for the human-centered manipulator. The first question to be addressed is how to translate our performance index into a desired closed-loop response. To answer this question we must map our performance index to a desired function of position errors and then formulate a desired closed-loop response that minimizes this function of position errors. We must do this because the entire control design effort for the human-centered manipulator is to minimize error between human's desire for position and the actual chair/bed position and it is our goal to generate a response that the human is most comfortable. As mentioned before the minimum energy performance index is defined by

$$J = \int_0^\infty |F_h|^2 \, dt \tag{6-1}$$

Assuming that the human can be modeled as a proportional controller we can say that minimizing J is equivalent to minimizing

$$J = \int_0^\infty |\theta - \theta_{des}|^2 \, dt \tag{6-2}$$

Now we can generate a desired closed loop response that minimizes (6-2). The structure of our desired closed loop will be chosen to be the same as the structure of our closed loop system so we can utilize the mathematical tools of MRAC.

6.3.2 Human Instrumentation as Feedback Signal Source

This research work emphasized the use of an adaptive interpreter to sense human desires for position of the backleaf of the reconfigurable bed/chair system and tuning the dynamic response of the human-centered manipulator to minimize human effort in the control of the system. This scheme required the inference of human muscle exertion from contact force measurements taken with conventional load cells as instruments. To make this inference required the estimation and compensation for gravity load which is not a perfect process and can degrade system performance. A more sophisticated system of measuring muscle force in a more direct fashion has the potential to improve system performance and provide a more accurate measurement of human signals sent to the chair via abdominal muscle exertion.

6.3.3 Hidden Markov Model as Estimator and Interpreter

In this work linear filters were utilized to make up the controller for the human-centered manipulator. However there is no reason that the interpretive controller need be built on these elements. Advanced estimation techniques such as the Hidden Markov Model are structured in a manner similar to the problem of the human-centered manipulator and the application of this technique would be an interesting area of research.

6.3.4 Exploration of Coordinated Multi-DOF Servoing (Surface Wave Actuator)

An additional limitation of the reconfigurable bed/chair system is the limited number of degrees of freedom of the mechanical system. The human body has a high number of degrees of freedom and the 5-DOF system is unable to physically interact with many of the human's degrees of freedom. A new high dimensional surface wave actuator system is being explored that can better accommodate the human body shape. Although the workspace of this system must be limited, if used in combination with the reconfigurable/bed chair structure a wide variety of human-centered manipulations can be achieved. For example rolling of the patient on the bed/chair system can be achieved. Adjusting the points of support of the human to prevent bed sores can be achieved. Many applications that require manipulation at a smaller scale can be achieved by this system.

6.3.5 New Applications for Interpretive Control Methodology

Using the adaptive interpretive control framework illustrated in Chapter 5 of this thesis many other task objectives could conceivably be tackled. Simply by redefining the task and altering the controller structure to achieve this task other applications are conceivable. For example, by replacing the admittance control structure with and impedance control structure, specific servo impedance can be generated by the 5-DOF reconfiguable bed/chair system. The application for this could be in exercise and rehabilitation where a specific impedance to human movement is prescribed and executed by the machine servo system and the human exerts muscle force against the servo for muscle conditioning and maintenance of joint and muscle flexibility. Possible control objectives include evening the load distribution exerted by the bed/chair upon the human, adjustment of the surface contour to maintain the human spine in a straight position, and stimulating the body surface to relieve pain. Additional exercise and rehabilitation applications exist by utilizing the servoing capability of this system to provide a set impedance to human motion for muscle strengthening and flexibility. In the future a design methodology will be formulated that will guide mechanism, actuator, and sensor choices for multifunctional machines that achieve a wide range of goals with identical hardware, but altered information management and decision structure.

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