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**IMECE2021-71487**

## **IMPROVING THE PERFORMANCE OF AMBULATORY GAIT TRAINING SYSTEM FOR REHABILITATION BY MECHATRONICS AND DESIGN SIMULATION**

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### **ABSTRACT**

*This paper addresses the design procedures and simulation results from the mechatronic model of the rehabilitation equipment, which can improve the functionality and precision of the ambulatory gait training system. The distinguishing feature of mechatronic systems is the achievement of system functionality through intensive integration. The paper demonstrates how the mechatronic design modeling has helped improve the design and performance of the new rehabilitation equipment built by the authors and is known as Navigaitor. The Navigaitor is designed to aid the patients who need to improve their balance and walk. The mechatronics aspects allow a better understanding of the dynamic behavior and interactions of the components. Depending on the severity of the patient's injury (stroke survivor, Parkinson, etc.), the oscillatory motion can range from uniform to non-uniform. The motion needs to be converted from the oscillatory sinusoidal motion of the patient into linear motion that the system can follow the patient with minimum lag and maximum stability. The data acquired during the training stage showing a different rate of recovery and response assists the system designers and thereby provides input to fine-tune the system and upgrade the control requirements.*

**Keywords:** Gait Training, Ambulatory Rehabilitation Systems, Mechatronics design, Navigaitor

### **1. INTRODUCTION**

The ambulatory suspension system is a device that is being used by physical therapists during physical therapy of the patient who suffers from musculoskeletal disabilities, injuries, diseases, muscle weakness, or surgical procedures. This device helps patients to recover from their illness sooner. The ambulatory

system supports body weight and keeps the patient from falling when exercising. Since this system supports patients from falling, it is easier for patients to gain confidence in exercise and strengthen their muscles sooner than when such a device is not used in the therapy.

However, early gait training in the in-patient unit is challenging for patients with severe impairment due to balance problems and increased risk of falls. Fear of falling is experienced both by the patients and the therapists and may significantly influence mobilizing stroke patients with severe deficits. Several different electromechanical assistive gait training systems are available for relatively more impaired patients, including bodyweight support using a harness and robotics-assisted systems [1]. Most commercially available weight-support systems are static and cannot adjust the vertical axis, which only allows mobility training from a standing position and limits vertical movement of the center of mass. Therefore, these systems may not allow "progressive gait training" starting from sitting to stand, transferring, walking on a flat surface, and walking on-ramp and stair negotiation. In addition, restriction on the center of mass movement may prohibit a natural pattern of ground-reaction force and gait characteristics [2]. Some examples of such systems are:

- **Biodex Un-weighting System:**

This device incorporates a dynamic suspension system that accommodates the vertical displacement of the center of gravity that occurs during normal gait. The off-loading mechanism maintains constant force by dialing the amount to off-load. This device does not allow for vertical movements, and it requires another person to assist the patient.

- **Lokomat System:**

Lokomat is considered as a device for robotic therapy for neurological movement disorders such as those following a stroke, spinal cord injury, multiple sclerosis, brain injury. An automated gait orthosis device supports the motion on a treadmill. It is based on the concept of a continuous repetition system for neurological patients to re-learn activities of daily living. It requires the assistance of one therapist.

- **ZeroG System:**

Zero-G system is a bodyweight support system that rides along a driven trolley attached to an overhead rail system; system typically attached to ceilings 9'+ high but can be designed without ceiling integration.

- **KineAssist Walking and Balance System:**

This is a robotic device and consists of a hip brace and harness that connects to an actuation system. It provides partial body weight support and postural torques on the torso while following the patient's walking motions over-ground in forward, rotation, and sidestepping directions. It assists patients to walk forward and backward, climb steps, step sideways & regain balance, strength, and mobility.

- **Autoambulator:**

This device is targeted for patients who have trouble walking and provides upright posture with a harness to suspend the patient over the treadmill. It provides robotic assistance to simulate normal walking motion. Although there has been scientific and clinical effort to provide effective interventions for gait among stroke survivors, gait training in patients with severe impairment remains challenging. Stroke survivors with a severe deficit are at risk of various adverse outcomes, including medical complications due to immobility and falls.

- **Navigaitor:**

The Navigaitor is an ambulatory suspension and rehabilitation apparatus system designed and experimented with by the authors at the therapy gym of the inpatient rehabilitation unit at a New York hospital in collaboration with the authors. It is a new device for research and clinical applications. Patients with neurological or musculoskeletal injuries, diseases, or muscle weakness can use it for physical therapy and exercise. Navigaitor enables exercise and movement training in all three planes of motion without the risk of falls and injuries. These features make the are possible because of the mechatronic design methodology.

### 1.1 Novel Features of Navigaitor

Navigaitor is a novel ambulatory gait training equipment that was designed to improve balance. It has been used selectively in patients with severe gait dysfunctions who required at least moderate assistance of 1 person (physical therapist) for walking initially. This device can help patients, such as stroke survivors who suffer from impaired gait function in the early stages of recovery. The equipment is comprised of a

dynamic weight-supported gantry training system, which provides motion in the horizontal (x, y) plane and vertical axis (z). The device acts as an automated support structure for patients by providing support in a full range of motion, allowing ambulatory impaired patients to rehabilitate under the supervision of a physical therapist safely. As the patient walks around, within the confines of the room-sized gantry, the hoist will follow the patient around. If ever the patient experiences a fall, the hoist system would keep the patient in place. The sensors are integrated into the system to ensure the required control accuracy and precision combined with enhanced motion dynamics. The oscillatory type of displacements characterizes the general motion of the patient. The control program uses a visual block programming simulation tool to interface with the hardware for real-time simulation and testing [3][4].

The research results demonstrate how it is possible to optimize the design of the structural components, the construction of the feed drives, or the controller strategy using the hardware-in-the-loop concepts. The mechatronics aspects allow a better understanding of the dynamic behavior and interactions of the components. Depending on the severity of the patient's injury (stroke survivor, Parkinson, etc.), the oscillatory motion can range from uniform to non-uniform. The motion needs to be converted from the oscillatory sinusoidal motion of the patient into linear motion that the system can follow the patient with minimum lag and maximum stability. The design procedures help in optimizing and identifying the fall prevention criteria.

Fall prevention is implemented at several levels with a mechatronic control. If the rate of change exceeds the prescribed limit, the system locks the system at a fixed position. The mechatronic force feedback system successfully addresses several challenges that are faced in the stair climbing process. It is necessary to perform optimal system tuning to produce high precision control requirements. The experiments done on the Navigaitor system with therapists demonstrated progressive gait training from sit to stand to walk on stairs. The system assisted the patient in building confidence and provided an opportunity for them to balance themselves. The different components of mobility (standing, turning, straight walking, or side walking) have a different rate of recovery or response to the training and balance. The data acquired during the training stage showing the different recovery rates and responses assist the system designers and thereby provides input to fine-tune the system and upgrade the control requirements.

## 2. DESIGN METHODOLOGY

### 2.1 Mechatronic System Design

Gait impairment is a significant contributor to functional disability, and many stroke survivors see gait improvement as a paramount goal in the rehabilitation process. Navigaitor helps the patients learn to walk again after serious surgery or disability. The system relieves a certain percentage of body weight by carrying the patient in a harness attached to a hoist. The hoist is actively controlled using feedback from strain gauge sensors. As

the patient walks around within the confines of the room-sized gantry, the hoist will follow the patient around. The overhead gantry is motorized in the X and Y directions. The closed-loop motor control reacts to feedback from multi-axis tilt sensors on the hoist line. The modules are chosen to interact with the rehabilitation walker sensors and handle the motor drive output signals [5][6].

## 2.2 System Constituents

Figure 1 illustrates the overall structure of the gait rehabilitation system. The apparatus consists of a support structure with I-beams, bridges. The carriers mounted on the bridge are free to move in XY planar region. The suspension system provides the Z-motion with a self-locking planetary gear-driven electric motor that can maintain a constant or a variable tension in the vertical direction. The system that provides Z-motion has a spreader bar and a tilt sensor that monitors excess motion. The Z motion system consists of the Z-axis force feedback closed-loop control system. The Z-axis and XY-axis systems are integrated into a multi-axis control system, as shown in Figure 2.

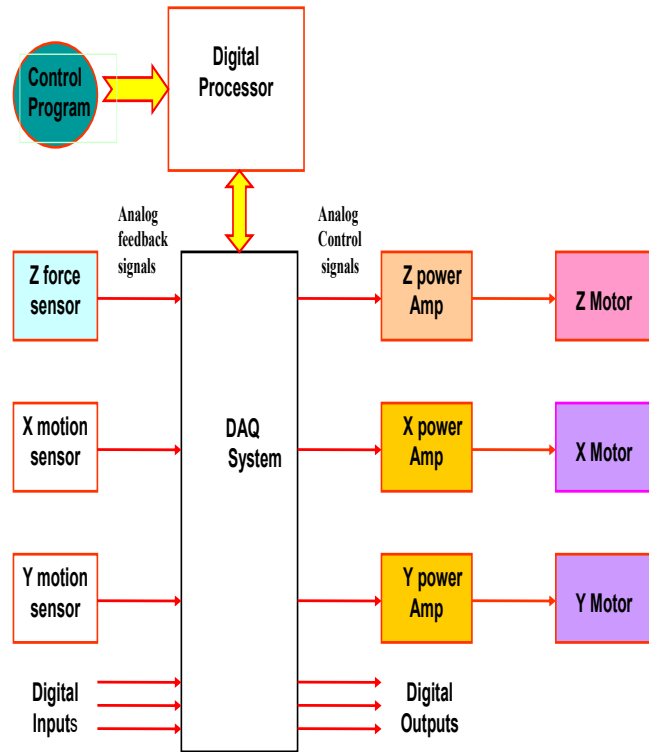


Figure 1: XYZ Control System.

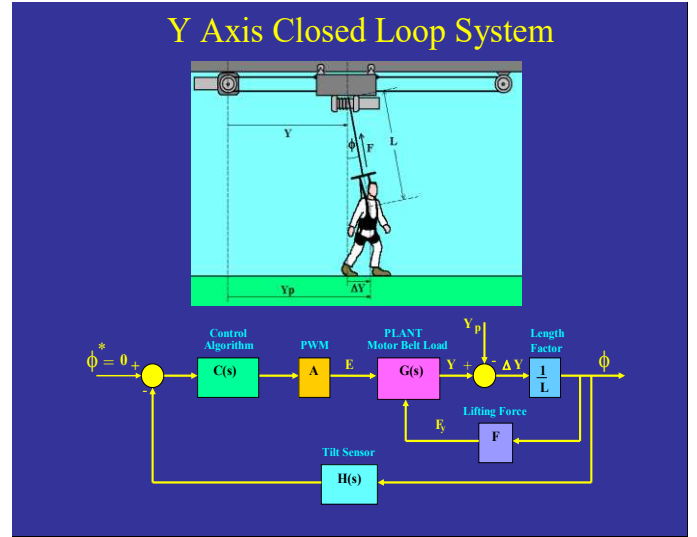


Figure 2: Y-AXIS Control Loop.

## 2.3 XYZ Motion System

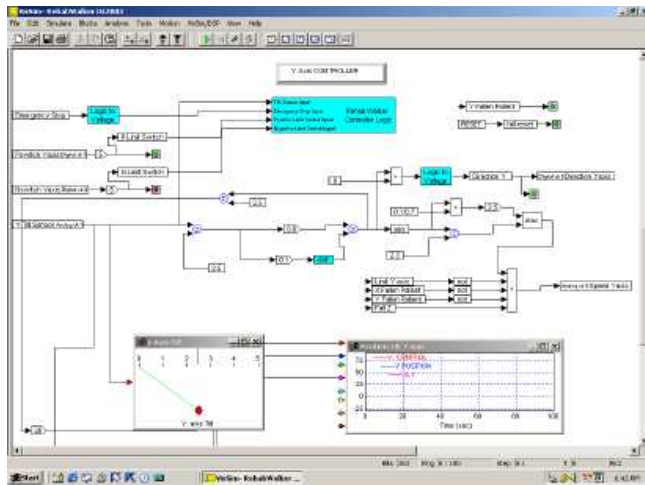
The control program uses a visual block programming simulation tool to interface the hardware for real-time hardware-in-the-loop simulation and testing. The system utilizes three variable-speed motors that dynamically track the patient's position with a combination of custom-built electronic sensors. The Z-axis-controlled variable (vertical force or tension) is measured with a load cell and bridge amplifier assembly. The X and Y-axis controlled variables (direction of motion) are sensed with a custom-built accelerometer-based tilt sensor and custom-built feedback amplifier assembly. The control system is developed with features that include manual and automatic control sequences and an emergency mode that utilizes "smart sensing" to determine when a patient falls or loses his or her balance. The system then stops, locking the position of the three dc motors, thereby supporting the patient until the therapist can assist the patient. A control system of the type proportional and derivative is employed [7][8].

An oscillatory type of displacement characterizes the human gait motion profile. Depending on the severity of the patient's injury (Stroke, Parkinson's), the oscillatory motion can range from uniform to non-uniform. Therefore, the motion needs to be converted from the oscillatory sinusoidal motion of the patient into a linear motion such that the system can follow the patient with minimum lag and maximum stability. A lead-lag controller and a leading offset type of controller have been implemented to achieve the desired motion characteristic of the system. In addition to a system gain proportional to the angle induced by the patient, an angle offset is introduced to give a motion lead in the intended direction in which the patient is traveling. In this manner, the oscillation characteristics induced by the patient are minimized.



## 2.4 Modification of Algorithm to improve the control system performance for XY movement.

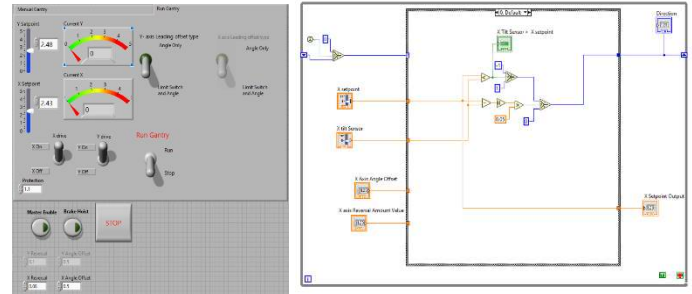
The purpose of this algorithm modification was to enable the system to start the motion with small tilt angles. Such capability was not achieved with the PD controller despite the changes made. This algorithm was added at the output of the PD controller (See Figure 3) and consisted of a logic comparator and a function block "max," which outputs the maximum value of its two inputs. When the output of the PD controller reaches a small value (0.1/0.7) corresponding to an angle of about 1 degree, the comparator outputs a logic 1, which is converted to 2.5 volts. This value is selected by the block "max" to drive the motor. Because of the filtering, the output of the tilt sensor has been delayed and still does not reach its full voltage. If the patient keeps walking, the total voltage is soon reached, and the block "max" switches to this greater voltage, so the PD compensator takes over the control of the motor.



**Figure 3: Modification of Program for Improvement of XY Axis Motion.**

A lead-lag controller and a leading offset type of controller have been implemented to achieve the desired motion characteristic of the system. In addition to a system gain proportional to the angle induced by the patient, an angle offset is introduced to give a motion lead in the intended direction in which the patient is traveling. In this manner, the oscillation characteristics induced by the patient are minimized. Figure 4 shows the modified algorithm for lead-lag and leading offset type controllers.

Thus, the modified algorithms allow the patient to start the motion sooner and in an effortless manner.



**Figure 4: Implementation of Leading Offset Type Controller Algorithm.**

## 2.5 System Development for Fall Prevention

The fall prevention criteria for this research are implemented on several levels. First, the XYZ-Axis force feedback control loop was designed with an integral method of capturing a patient during a sudden fall. The force measuring system contains a control algorithm that senses the rate of change of the measured variable and locks the system at a fixed position if the rate of change exceeds the adjustable prescribed limit. The algorithm must be manually reset before the automated support algorithms can resume their automated functions.

The mechatronic system design procedures help in optimizing and identifying the fall prevention criteria. The Z-axis force feedback control loop is designed with an integral method of capturing a patient during a sudden fall. The force measuring system contains a control algorithm that senses the rate of change of the measured variable and locks the system at a fixed position if the rate of change exceeds the adjustable prescribed limit. The algorithm is reset before the automated support algorithms can resume their automated functions.

An emergency stop button allows the patient or attendant to stop the automated process and lock the patient's position if an unsafe condition is detected. In addition, the Z-axis lifting mechanism is provided with a three-stage planetary gear train that is inherently self-locking and prevents a patient from falling in the event of a power failure. Figure 5 shows a Navigaitor system installed in a laboratory.



**Figure 5: Navigaitor Testing & Experiments.**

Force feedback control during stair climbing presents several challenges. First, the control system must be designed to rapidly anticipate step or rapid input changes without over or under compensating.

The entire drive system must respond to these sudden changes rapidly with a minimum delay or "Lag" in the system's response concerning disturbances. The control algorithm must be carefully tuned to maximize the gain for the control system to respond to the needs.

## 2.6 Modeling of the Plant for XY Motion

**Table 1: Control Parameters.**

|             |                           |
|-------------|---------------------------|
| L           | Length of Cable           |
| F           | Lifting Force             |
| Y           | Carriage Position         |
| $\emptyset$ | Tilted Angle              |
| $\Delta Y$  | Walking Distance          |
| H(s)        | Tilt Sensor               |
| C(s)        | Control Algorithm         |
| PWM         | Output Amplifier          |
| G(s)        | System Motor Belt Carrier |

The ambulatory control system aims to control the motion of the carriage so observe the patient's horizontal movements with maximum accuracy. An example of the analysis of variables involved in Y-direction is shown in Figures 2 and 3. The tilt sensor measures the control variable ( $\emptyset$ ). Control Algorithm C(s) process the difference or error. As an example of a hardware-in-the-loop system, motion control is achieved by simulation software and associated control scheme. In the control system block diagram, the main feedback of the system is provided by the tilt sensor. Force feedback is provided as  $F_y$ . The plant consists of the DC motor with its gearbox and pulley, the belt, and the carrier. The motor has a rotor with a moment of inertia  $J_1$  and a viscous friction  $B_1$ . The gearbox has a ratio  $n = \frac{1}{15}$  and the pulley a radius  $r$ . When the motor shaft rotates an angle  $\emptyset_1$ , the pulley turns an angle  $\emptyset_2 = n \emptyset_1$ . The belt is assumed to be like a spring with constant  $K$ . The carrier has a mass  $M$  and a viscous friction  $B_2$ . When a voltage  $E$  is applied to the motor, an armature current produced is determined by Equation 1.

$$i = \frac{(E - e_m)}{Ra} \quad (1)$$

where  $Ra$  is the armature resistance and  $e_m$  the motor back electromotive force as shown in Equation 2.

$$e_m = K_b w_1 \quad (2)$$

$K_b$  is a motor-dependent constant and  $w_1$  the shaft angular velocity. The current  $i$  creates a torque  $\tau$ . This torque is used to overcome the inertia and friction of the rotor, and to drive the motor load. The torque is represented in Equation 3.

$$\tau = J_1 \left( \frac{d^2 \theta_1}{dt^2} \right) + B_1 \left( \frac{d \theta_1}{dt} \right) + \tau_L \quad (3)$$

Where  $\tau_L$  It is the torque required to pull the carrier. (Equation 4)

$$\tau_L = F_L n r \quad (4)$$

And  $F_L$  It is the traction force applied to the belt. (Equation 5)

$$F_L = K(y_2 - y) \quad (5)$$

Where  $(y_2 - y)$  It is the stretch of the belt.

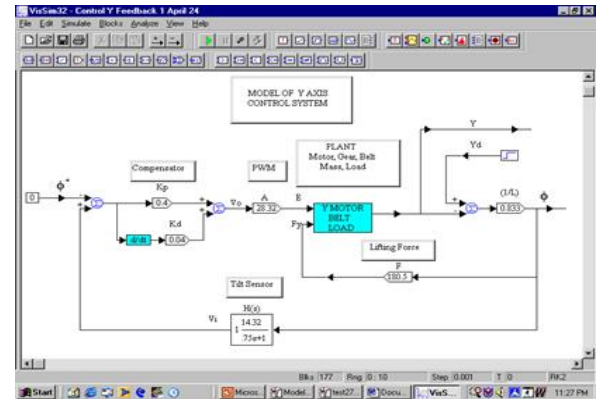
This force describes the mass-spring system formed by the carriage and the belt. (shown in Equation 6)

$$F_y = M \left( \frac{dy^2}{dt^2} \right) + B_2 \left( \frac{dy}{dt} \right) + F_L \quad (6)$$

$F_y$  It is the horizontal component of force.

## 2.7 Simulation of the Control System

The whole system consisting of the plant, sensors and actuators was simulated using EMBED simulation program. The system simulation diagram is shown in Figure 6. The belt load, tilt sensor, and proper blocks replaced amplifiers. L and F variables were considered constants with the values:  $L=1.2m$  (3.9ft) and  $F=180.5N$  (40lb).



**Figure 6: System Simulation.**

These values were considered the average values required for most patients (Our real performance tests were made mainly with these values). The simulation was made using, as the first approach, a PD compensator. The proportional gain  $K_p$  was set to 0.4, and the derivative gain  $K_d$  first was set to zero and then to 0.04. The results of the simulation are shown in Figures 7 to 9. They are compared with the results of real tests.

In the simulation, a step signal with an amplitude of 0.5 was applied as a disturbance  $Y_p$ . In the actual test, a person supported

by the cable moved a 0.5m step sharply forward. The position Y and the angle  $\theta$  are shown simultaneously in each plot scaled so that each vertical division represents either 0.1m or 2 degrees. In the case of  $\theta$ , zero degrees are at the center of the scale.

## 2.8 Force Control Compensation during Stair Climbing

Force feedback control during stair climbing presents several challenges. First, the control system must be designed to rapidly anticipate step or rapid input changes without over or under compensating. Second, the entire drive system must respond to these sudden changes rapidly with a minimum delay or "Lag" in the system's response concerning disturbances. Finally, the control algorithm must be carefully tuned to maximize the Proportional Gain and Derivative or Rate Gain for the control system to respond in such a way. Tests were conducted on the real system to optimize these parameters and are presented in the next section.

The operational flow chart of Navigaitor is shown in Appendix 1. The flow chart illustrates the step-by-step algorithmic modification carried out through testing the device.

## 3. RESULTS AND DISCUSSION

### 3.1 Algorithmic Modification Through Testing

The unique feature of the design is the modification of the algorithm through testing of patients. When using the Navigaitor, the patients will experience a certain amount of comfort. By using the leading offset function in the control system, the patients put less effort into making the system move. The measure of comfort for patients who are fragile is very important aspect as they traverse in a XY plane. The design procedures help in optimizing and identifying the fall prevention criteria. Fall prevention is implemented at several levels with a mechatronic control. If the rate of change exceeds the prescribed limit, the system locks the system at a fixed position. The mechatronic force feedback system successfully addresses several challenges that are faced in the stair climbing process. First, it is necessary to perform optimal control system tuning to produce high precision control requirements. The experiments on the Navigaitor system done with therapists demonstrated progressive gait training from sit to stand to walk on stairs. The system assisted the patient in building confidence and provide an opportunity for them to balance themselves.

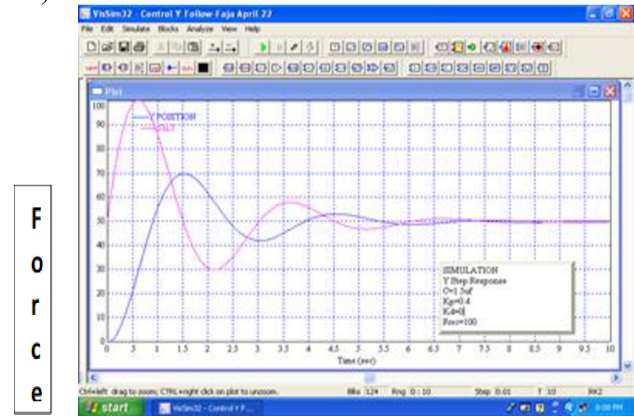
The different components of mobility (standing, turning, straight walking, or side walking) have different recovery rates or responses to the training and balance themselves. The data acquired during the training stage showing a different rate of recovery and response assists the system designers and thereby provides input to fine-tune the system and upgrade the control requirements (Figures 7 and 8).

Gait impairment is a significant contributor to functional disability, and many stroke survivors see gait improvement as a crucial goal in the rehabilitation process. The mechatronics aspects allow a better understanding of the dynamic behavior and interactions of the components. Depending on the severity of the patient's injury (stroke survivor, Parkinson etc.), the oscillatory

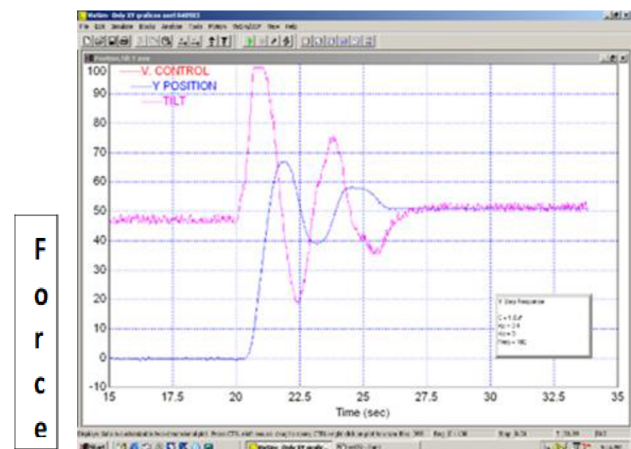
motion can range from uniform to non-uniform. The motion needs to be converted from the oscillatory sinusoidal motion of the patient into linear motion that the system can follow the patient with minimum lag and maximum stability.

### 3.2 Z-Axis Results and Modification of Algorithm to Improve System Performance.

For optimal tuning, the gain of the control system must be as high as possible without causing control system oscillation. However, during testing of the z-axis control system, integral gain during loop tuning produced delays in system response. For this reason, the control loop was implemented for the Z-axis to produce a parallel proportional-feed forward derivative control loop effectively. For support of 40 lbs, Figure 9 shows how the duty cycle, which controls the speed of the Z-axis motor, responds to the changes in load as the patient traverses a flat plane, then goes up and downstairs and finally simulates a fall. During the fall sequence, the prescribed limit of the rate of change in force is detected, and a constant duty cycle value is output to the motor, which locks the system in position (Figure 10).



**Figure 7: Step Response of Simulation.**  
( $K_p = 0.4$ ,  $K_d = 0$ )



**Figure 8: Real Time Step Response.**  
( $K_p = 0.4$ ,  $K_d = 0$ )



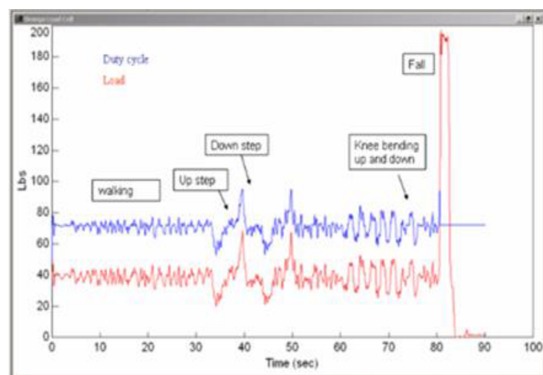


Figure 9: Z-Axis Control Response.

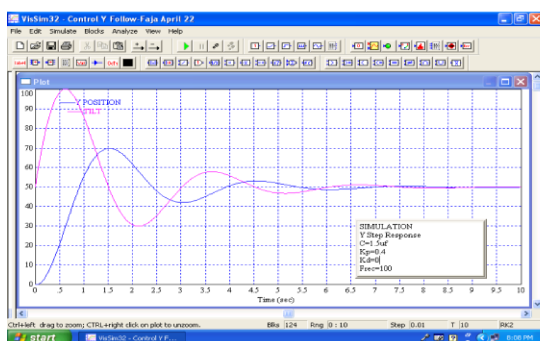


Figure 10: Model Step Response Due to Disturbance.  $\Delta Y=0.5$ ,  $P=0.4$ ,  $D=0$

### 3.3 XY-Axis

Initial studies were focused on observing and measuring the system response for one axis. The tests and results shown here are for the y- axis. Figures 10 and 11 show the system response due to a step input. The step input is represented as a disturbance with a person taking a step of 0.5 meters in length. The displacement of the y-axis carriage and the tilt angle are recorded. A proportional gain of 0.4 and a derivative gain of 0 were used in this case.

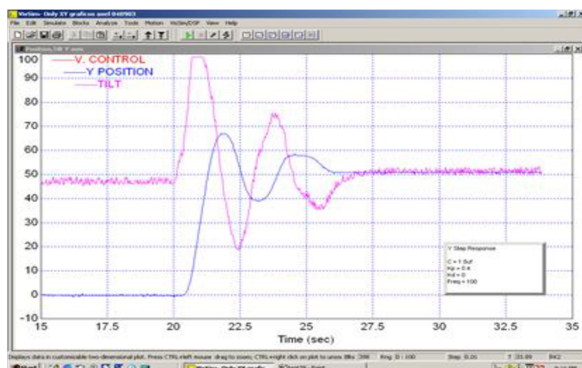


Figure 11: Real-Time Step Response Due to Disturbance.  $\Delta Y=0.5$ ,  $P=0.4$ ,  $D=0$

Both the model and real system responses correlate with each other. As can be seen in this case, a large tilt angle is required for displacement. Also, the system response goes through several oscillations before it stabilizes at a steady state.

Given this system response, a series of studies would have to be conducted to find the optimum proportional and derivative gain parameters such that (a) The system response oscillations are attenuated. (b) The tilt angle required to set the system in motion is minimized so that less effort is required on the part of the patient when walking.

The best system response that meets the above requirements was achieved using a proportional gain of 0.7, a derivative gain of 0.15, and a time constant of 2. Figure 11 shows the system response results with optimum PD parameters under normal walking conditions. The results show that the oscillations are attenuated and that the tilt angle required to set the system in motion is reduced. The research results demonstrate how it is possible to optimize the design of the structural components, the construction of the feed drives, or the controller strategy using the hardware-in-the-loop concepts.

### 3.4 Parameters of Safe Gait Training with Navigaitor

Although there has been scientific and clinical effort to provide effective interventions for gait among stroke survivors, gait training in patients with severe impairment remains challenging. Stroke survivors with a severe deficit are at risk of various adverse outcomes, including medical complications due to immobility and falls. In addition, the length of stay in the rehabilitation unit, the rate of discharge to the subacute setting, and subsequent healthcare costs are higher among this group than patients with mild deficits. However, this population is often excluded from clinical trials, and there is scarce literature available for mobility training in this group [9].

### 3.5 Patient Characteristics and Outcome Measures

The efficacy of this equipment was demonstrated in a series of experiments conducted at the New York hospital laboratory dedicated to rehabilitation. It is the hospital where the authors were conducting collaborative work. Eight acute stroke survivors with severe gait dysfunction underwent gait training with Navigaitor during the physical therapy session. All subjects had a Functional Independence Measure (FIMTM) walking sub score of 1, defined as the inability to walk more than 50 feet and require more than one (1) person assist. The mean age was 65.8 years, with 50% male. Most of the patients [6,7] had left hemisphere involvement. Seven out of 8 patients had infarct, and only one (1) received tissue plasminogen activator (t-PA) intervention. In each gait training session with Navigaitor, self-selected overground gait velocity (SSV) and timed up and go test (TUG) was measured with the Navigaitor system. For SSV, subjects were timed with a stopwatch as they walked a 3-meter walkway at their self-selected comfortable walking speed in two trials from which the mean value was calculated. The TUG was measured with a stopwatch as the stroke survivors stand up from a wheelchair, walk 3 meters, turn around, walk back to the chair,

and return to a seated position [10]. Total and Motor FIMTM data were collected as well. Acceptance of patients and therapist was also obtained during each session and after the last session with an open-ended question. Any adverse events, including falls, discomfort, dyspnea with exertion or harness, skin breakdown, were also recorded after each training session.

### 3.6 Training with Navigaitor [11]

Patients received 2-3 sessions of gait training per week with Navigaitor for 2-4 weeks (12-26 days, average 18.5 days). Each session was 30 minutes long. Patients received conventional therapy including progressive gait training; transfer and bed mobility initially to gait training without body support as progressed, strengthening, endurance exercise during the rest of the therapy session. Training session using Navigaitor began after donning the safety harness which was attached via a cable to the hoist. Progressive gait training started from sit to stand. Then, the patient stood up with assistance by the Navigaitor as needed.

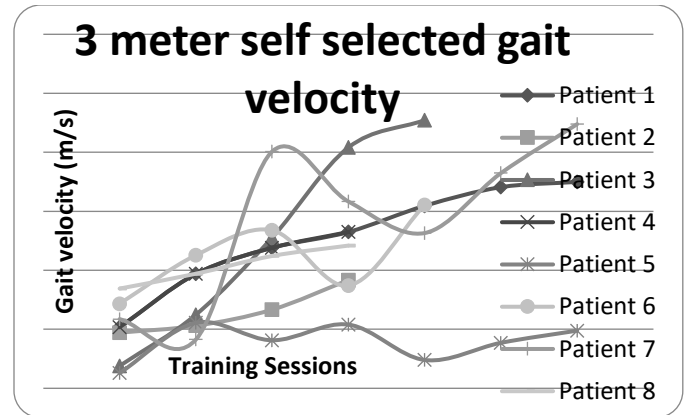
Once patients balanced themselves in standing position, walking on a flat surface for 10 feet then turning and walk another 10-20 feet before sitting back to the chair. Turning was 90° (left or right), 180° (reversed direction), or free angle (direction). Patients repeated this training and gradually increased the distance of walking. As patients progressed, additional training, including trunk stabilization, lateral weight shifting, balance reaction, side walking, walking on an irregular surface (carpet with/without obstacle), ramp, and stairs were added. Throughout clinical training, patients were accompanied by a physical therapist who provided clinical cues or assistance, as required. Assistance varied from contact guard to maximum assist to maintain balance, trunk alignment, and advance the paretic limb.

### 3.7 Gait Parameters with Navigaitor

During training sessions, there was no incidence of falls reported despite multiple episodes of loss of balance. No patient reported discomfort wearing the harness. All patients stated that they felt comfortable training with Navigaitor after 2-3 sessions. No patient developed any significant medical complications such as deep vein thrombosis, pulmonary embolism, pressure ulcer, pneumonia, subsequent Stroke, or acute coronary syndrome during the rehabilitation stay. The therapist reported a reduced need for additional staff assistance in initial gait training, decreased fear of patients' falling, and increased confidence in advancing the training protocol for each patient. Therapists also expressed the willingness to utilize Navigaitor for training patients in the future [12] [13].

Figure 12 shows the data of the 3 meters self-selected gait speed (SSV) changes throughout the training sessions. Most patients achieved significant improvement in 3 meters SSV. The 3 meters SSV improved from 0.05 meter/second (m/s); 84.9 seconds (sec) to 0.12 m/s (25.1 sec). Initially, all patients required rolling walkers, and 7 out of 8 were only able to walk in parallel bars. At the end of the rehabilitation stay, 1 of 8 did not use any assistive device, 2 of 8 advanced to walk with hemi

walker cane or quadripod canes. There was a significant improvement in endurance reflected by distance as well. FIMTM total and motor scores also improved from 56.8 to 83.2 and 30.3 to 54.4, respectively. Three out of 8 patients were discharged home.



**Figure 12: Changes in 3 Meter Self-Selected Gait Velocity Over the Training Course.**

### 3.8 System Improvement using Test Results

In this batch of experiments, we have identified feasibility, patients' and therapists' response to the device, and safety of gait training using Navigaitor system. Navigaitor system is unique because it allows "progressive gait training" from sitting to stand to walk on stairs. All eight patients made progress in walking using Navigaitor and eventually walk without the harness system. A partial weight-supported harness system was reported to enable early gait training in severely affected stroke survivors by providing trunk and pelvis control [14], as shown in our series. Improvement in standing balance control was reported to be more critical than synergism and muscle strength of the paretic leg in regaining gait [12]. We hypothesize that the Navigaitor system assisted the patient in building confidence and provide an opportunity for them to balance themselves. Gait velocity with Navigaitor increased in all patients. Two patients progressed from using a rolling walker to hemi cane, and one patient was able to walk without an assistive device. By the end of the training session, all patients could ambulate without a BWS harness with a different level of assistance.

Early gait training may play a role in preventing medical complications secondary to immobility, such as deep vein thrombosis and pressure ulcer formation. None of the patients in our series had such complications during the rehabilitation stay. All patients trained with the Navigaitor stated that they did not fear falling during training with the Navigaitor expressed confidence in training. From the therapist's point of view, Navigaitor increased the physical therapist's confidence by eliminating the risk of falling and allowed gait training for the patients at the very early stage of inpatient rehabilitation. The different components of mobility (standing, turning, straight

walking, or side walking) have a different rate of recovery or response to the training and balance themselves [15][16].

The trials done with Navigaitor helped the gait therapy sessions from sitting-to-stand-to-walk on stairs experiments and provided insight into the mechatronics design. The data acquired during the training stage showing a different rate of recovery and response assists the system designers and thereby provides input to fine-tune the system and upgrade the control requirements. The hardware in the loop concept of mechatronics played a significant role in optimizing the control and sensing requirements and choosing optimized control components. Further, the system assisted the patient in building confidence and provide an opportunity for them to balance themselves. In summary, this investigation concludes that gait training can be carried out safely in stroke survivors using Navigaitor. The uniqueness of the Navigaitor system can be summarized as follows:

1. Mechatronics design provides the ability to transform an industrial gantry system into a gait monitoring system. The mechatronic approach promotes the use of commercial off-the-shelf components of sensors and actuators.
2. The Navigaitor enables movement training in all three planes of motion without risk of falls and injuries. It helps the user perform a regular walking pattern in a planar region rather than a straight line, as found in other systems. Motorized XY motion is used so that the patient can start, walk, and stop with minimal effort and maximum safety.
3. Lead-lag controller algorithm and leading offset algorithm help the patient's movement. The patients do not have to exert pressure on the cable as the control algorithm guarantees a smooth movement.
4. The apparatus can be configured to accommodate different therapy facilities that may require adjustments in the mechanical and computer systems to maintain uniform and consistent operation.
5. Navigaitor provides the ability to the patients to go up and down and climb stairs. Motorized Z-axis motion with self-locking allows vertical displacement under constant or variable tension.
6. Automation prevents falls and allows emergency stops.

#### 4. CONCLUSION

The results demonstrate that the design approach of Navigaitor using mechatronics and simulation allows a better understanding of the dynamic behavior and interactions of the components. The Navigaitor assists patient training in all three planes of motion without risk of falls and injuries. It helps the user to perform regular walking patterns in a planar region rather than a straight line, as found in other systems. The hardware-in-the-loop concept of mechatronics played a significant role in optimizing the control and sensing requirements and choosing optimized components that are chosen "off the shelf." The simulation data acquired during the training stage showing a rate of recovery and response assists the system designers in deciding

on the input to fine-tune the system and upgrade the control requirements. The results indicate that the Navigaitor can provide partial-weight support, progressive gait training and can assist the patients in building confidence.

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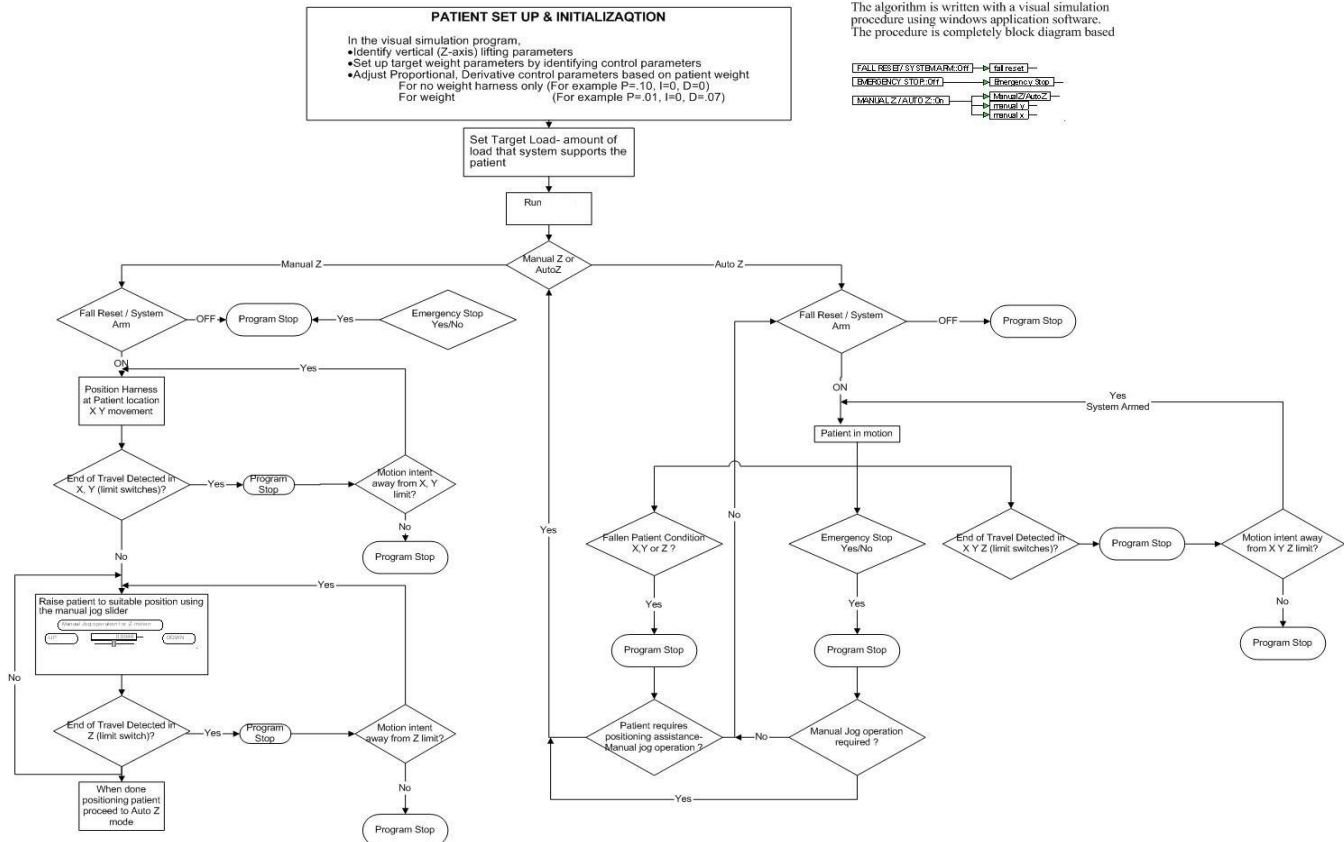
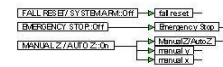
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# OPERATIONAL FLOW CHART OF AMBULATORY SUSPENSION SYSTEM

The algorithm is written with a visual simulation procedure using windows application software. The procedure is completely block diagram based



Appendix 1: Operational Flow chart of Navigaitor showing algorithmic modification through testing