Design and Implementation of a Mechatronic SmartBed for Improved Rehabilitation

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***Abstract*—Healthcare demand for hospital beds is a concern in both private and public institutions. Conventional beds are cumbersome and do not consider caregiver's health, nor patient's stress and discomfort, which have consequences on the rehabilitation process. For these reasons, a mechatronic SmartBed system is proposed, designed with a user-friendly interface that empowers the patient and caregiver to move the bed into complex positions that improves the person's quality of life and reduce the risk of death. In this paper, the details of the design and development process of the SmartBed, with special focus on the interactive user interface for controlling the system, along with preliminary results of the interaction between test subjects and the hospital bed is presented.**

I. Introduction

Currently, there is a high demand of hospital beds for patients in private and public healthcare institutions. Conventional mechanical/electrical medical beds are cumbersome, and are devoid of solutions to reduce injuries in the patient such as skin pressure ulcers caused by the lack of movement for a prolonged time, or prevent deaths caused by disorders such as sleep apnea. Bed positioning is performed with unfriendly interfaces, like mechanical handles or manual electronic controllers, making the action of changing positions tedious and awkward for the patient and the caregiver. Moreover, hospital beds do not provide friendly user interfaces to control positioning of the bed in order to ease simple tasks (e.g. watching TV, reading, or eating with an optimum body posture). As a result, these types of beds generate stress and discomfort to the patient while affecting the rehabilitation process of the health condition.

An adjustable bed, or more commonly known as hospital bed, is furniture with adjustable frames that hinges at the hips and knees of the patient to raise or low the legs and/or back. Most notable contributions to the design were the replacement of mechanical hinges with electrical actuators and the addition of a simple button control to energize the actuators [1]. Newer beds, such as those produced by Stryker [2] and the EPOSbed project [3], integrated electronic systems to measure and procure the patient's weight, and simplify the buttons mechanics with conventional touch screen panels; the University of New Hampshire has developed a hospital bed capable of monitoring blood pressure and breathing patterns [4] to respond to a possible emergency. Different control approaches for the embedded electronic hardware of the medical beds have been tested like: an FPGA based solution controlled by a brain-computer interface with SSVEP signals [5]; a multivariable control technique with TDD decoupling technique for better performance under uncertainty conditions [6]; and an autonomous navigation ability based on reaction algorithm for safe transportation of critical patients [7]. Nevertheless, these solutions were designed with an automatic furniture approach rather than an easy-to-use hardware/software interface for the involved stakeholders (patients, patient's family, caregivers and doctors). Additionally, the shared touching interfaces and controllers to manipulate the beds elevate the risk and possibility of patient-doctor/caregiver infections, producing a contaminated healthcare environment [8]. On the other hand, a solution for bedsore injury prevention with temperature sensors and IR proximity sensors is presented by Bandala et.al. [9]; for apnea sleep disorder, a solution with pressure sensors under the mattress of the bed is presented by Townsend et.al. [10]; Clifford & Gederi [11] manifest that sleep monitoring could be performed with fiber-optic-based pressure sensors for motion, audio recording for obstructive events from snoring, non-contact ECG (electrocardiogram) based on capacitive electrodes for hearth rate and respiration rate. These researches show the importance of monitoring the patient in order to reduce injuries and avoid fatalities produced by disorders.

Modifying a hospital bed to allow the automation and tracking of preconfigured positions, in combination with a smart and intuitive friendly user interface could highly improve the experience of the patient and ease the burden of the caregiver. The concept of a smart bed presents a potential solution able to monitor the patient movements while manipulating the shape of the bed, provide local or remote alarms for preset dangerous configurations detected (e.g. patient falling unexpectedly off the bed), and send information to the cloud to be accessed by the caregiver and/or patient's family remotely using mobile devices.

Therefore, in order to have hospital bed that covers various of the issues mentioned before, a Smart Mechatronic Bed for improved rehabilitation was developed. This equipment is able to: i) monitor patients position and motion locally or remotely; ii) provide both, patients and caregivers, an easy-to-use GUI (graphical user interface) with accurate data display

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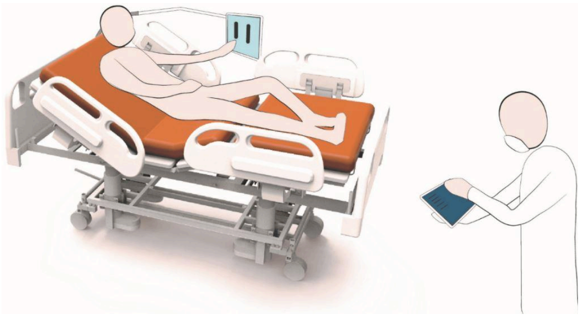


Fig. 1. SmartBed Concept Design.

and controls for bed positioning; iii) avoid patient-caregiver infection by contact with two independent controls; and iv) provide a sense of autonomy to the patient.

This paper presents the design and development of a mechatronic smart bed for medical rehabilitation and is organized as follows. In section I the importance of electrical/mechanical hospital beds is discussed. In section II the design criteria based on user requirements and medical regulations is described, and the development is defined. In section III an experimental setup for users experiences, alongside results in section IV, are evaluated. Finally, in section V the conclusion and future work of the present research and development are presented.

II. Design and Development

From the state of the art and current hospital needs, the requirements (II-A) and design assumptions (II-B) were evaluated to assess the design of the SmartBed, showed in Fig. 1, which was divided into 4 sections: mechanical design (II-C), electronic design (II-D), software design (II-E), and graphic user interface (II-F). The United States Food and Drug Administration (US FDA) Hospital Bed System Dimensional and Assessment Guide was used as reference for ergonomic design to reduce the chance of entrapment between the moving sections. Furthermore, each preconfigured position, as well as which articulations to implement, was designed keeping in mind seven standard medical positions for patients which are detailed in Table I.

A. Requirements

Bed monitoring allows the caregiver to keep track of bed positions and patient movement during certain time interval. This information is essential to prevent skin pressure ulcers caused by the lack of movement of the patient. Moreover, patient movement monitoring should be conducted in order to alert the caregiver in case the patient unexpectedly falls off the bed.

1) Functional Requirement (User): The caregiver should be able to access a list with the record of time and bed positions during the stay of the patient. In regards to patient movement monitoring, the user should be able to visualize the amount of movement of the patient and areas of the mattress where more movement activity is detected.

2) Functional Requirement (System): The software app should keep a local database with the information of bed positions successfully sent to the Main control circuit board and its corresponding time-stamp. On the other hand, the software app should receive weight data, from the force sensors beam located at the base of the bed, store it locally and display it in the form of a graph.

B. Design Assumptions

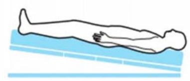
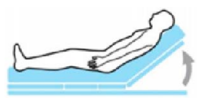
The system functionality and operability are based on the following assumptions and constrains:

1) Target users: Although the system will provide an intuitive interface, the successful operability will be constrained to adult users who have received proper training on how to use the software interface.

2) Operation environment: It is assumed that the overall system (mechatronic bed & table with software app) will operate in healthcare institutions under indoor environments.

3) Hardware compliance: The software app is constrained to operate with one specific SmartBed. In order to achieve successful operability, it is assumed that software app has been previously configured with the corresponding hardware of the mechatronic bed. On the other hand, the mechanical design must be implemented with the required security restrictions established by the US FDA.

TABLE I
Standard Hospital Bed Positions

Position	Description	Image
Trendelenburg	The head of the bed is lowered and the foot of the bed is raised	
Anti Trendelenburg	The head of the bed is elevated with the foot of the bed down.	
Fowler	The head of the bed is elevated 45-60 degrees.	
Gatch	The bed adjusts a joint, allowing the knees to be flexed	
Autocontorno	The head of the bed is elevated 45-60 degrees, while a joint is adjusted to allow the knees to be flexed and legs supported.	
Lateral	The bed tilts to the left or right deviating from the medial plane	
Standard	The bed is in its initial shape, allowing the patient to lay down in a neutral position.	

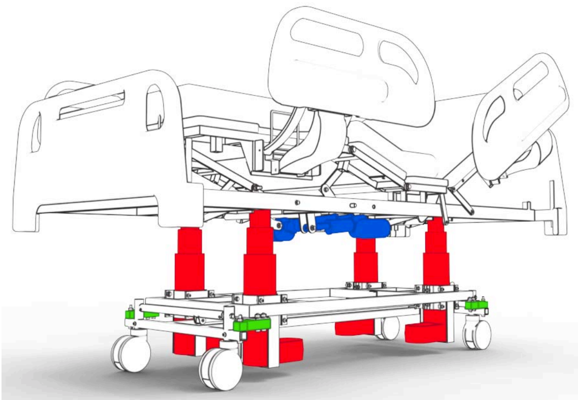


Fig. 2. Distribution of Actuators (red & blue) & Load Cells (green)

4) Connectivity: It is assumed that the software app has established a successful Bluetooth connection so as to send control commands to the physical SmartBed. On the other hand, it is also assumed that Internet connectivity has been established in order to sync data to a secure server.

5) Failsafe: In case of power failure, the system must have a battery with enough charge to place the hospital bed in a safe position for the patient. The SmartBed also must have compatibility with current commercial button controls to ease technological transition.

C. Mechanical Design

To achieve all possible movements with the minimum stress on the mechanical components, a four pillar approach was selected. Each pillar is a linear column actuator with a stroke length of 380 mm and a load capacity of 700 to 1500 N depending on the arm extension. These linear motors are attached to the bottom of the bed by compensator mechanisms to enable pitch and roll of the sommier. On the other hand, the head and foot section of the bed have a hospital grade linear actuator with a stroke length of 200 mm and 100 mm respectively. These actuators have a load capacity of 6000 N while pushing and 3000 N while pulling. Both are attached to hinges and rods to convert the translational movement to rotational without sacrificing torque.

With all six actuators working in conjunction, located as indicated in Fig. 2, the Smart Bed is able to perform all the basic movements without manual intervention. As a medical device, the actuators have included a safety emergency release to move each motor without electric power and to return to the standard position quickly. Due to the fact that each actuator does not provide position feedback, and in order to reduce costs of production, it was necessary to implement a different control system with some kind of feedback to accurately move the mechatronic bed as it was intended. The solution consists of measuring inertial sensors located at 3 key positions: header, footer and bed frame.

D. Electronic Design

Designed as a modular system, Fig. 3 shows the electronic components embedded on the hospital bed. Each module is placed on a custom designed mainboard as shown in Fig. 4. Every module is replaceable may one of them malfunction.

1) Load Cells Module: Four load cells, highlighted in Fig. 2 as green, are located at the base of the bed to measure the average gravity center of the patient as well as his historical weight. These sensors have a Wheatstone Bridge configuration and thus amplified before capturing the signal. Each beam has a maximum payload of 300 kg, with a nominal output of 2mV/V and an operation range of 5 to 12 VDC. By powering them up at 5V, a resolution of 0.033mV/Kg is achieved. The signal, amplified by 400 with an instrument amplifier, is read by a 14-bit resolution ADC. Each load cell is measured independently to enable complex data processing and the data is sent to a tablet for data storage and further analysis. Each measurement of the Load Cells are used to get a historic data of the patient's weight as well as the approximate location of the patient's center of gravity.

2) Motor Drivers Module: The linear actuators are driven by 3 dual motor drivers based on the VNH5019 dual motor driver chip which delivers a continuous 12 A at 24V per motor channel and enable the system to control accurately the speed and movement of each actuator. Nonetheless, as there is no feedback output from these motors, all the required information for a closed loop control is obtained by the three inertial sensors previously indicated.

3) Inertial Sensors Module: Three digital accelerometers with a current consumption of 23uA on reading, configured at 10-bit resolution with 4g, are located along the long axis of the bed to ensure that each section is inclined the specified amount with ground as reference. The header and footer section of the mechatronic bed is compared to the overall inclination angle of the system so as to the position of the patient does not change if a Trendelemburg or an Anti-Trendelemburg movement is issued while Fowler or Gatch is active. For example, if the Fowler position is requested, and then an Anti-Trendelenburg is queued, the length of the extended actuator on the header will correct itself to make certain that the angle of the Fowler section remains constant to the ground, regardless of the offset produced by the Anti-Trendelenburg movement.

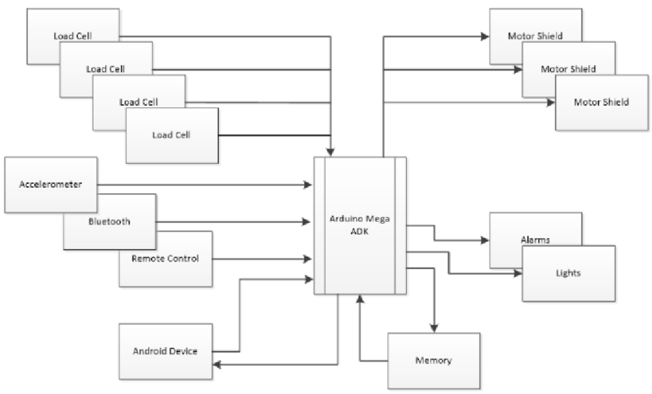


Fig. 3. Mechatronic Bed Modules

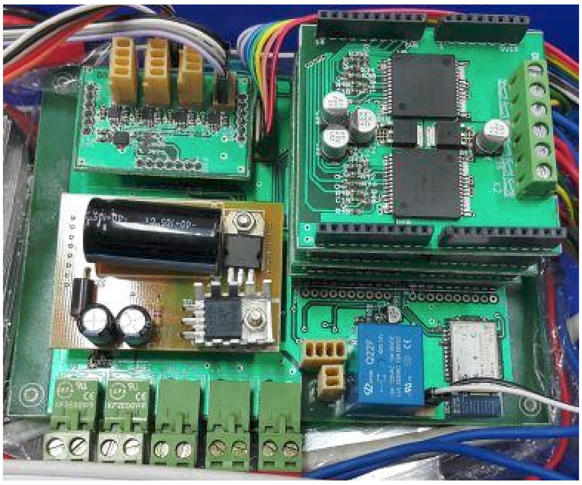


Fig. 4. SmartBed Main Board

4) Alarms and Lightning Module: The mechatronic bed is embedded with a bright white LED strip and a mechanical relay for lighting and alarms. On one side, the light shines on the floor as a leading light to aid the caregiver at night without obstructing the patient's comfort. It has configurable intensity levels depending on the needs of the user. On the other side, the relay is connected to the hospital alarms' grid to beckon the nurses when the patient has a need or an emergency has arisen. This audio feedback ensures that the signals would not go unnoticed and shortens the response time in case of an emergency.

5) Human-Machine Interface Module (HMI): Two tablets with Android's Operating System (OS) were proposed: a handheld sized USB connected tablet to be used by patients for simple commands and alarm calls, and a 10.1 inch Bluetooth ready tablet for the caregiver's usage. To enable the connection to the portable devices, a Bluetooth Slave module was setup with TTL-Serial communication and a simple frame commands. Furthermore, this module also has a connection to a standard hospital button panels to control the actuators manually. Further details on these HMI devices are presented on the next section.

E. Software Design

The software interface for controlling the SmarBed can be described by a software architecture, presented in Fig. 5, which consists of four layers staked from top to bottom: HMI layer, Application layer, Android OS layer, and Hardware layer. The HMI layer consists of a graphic user interface (GUI) that the user interacts with in order to control the SmartBed. The GUI contains graphical elements and interaction functionalities that are integrated to provide a comfortable experience to the user in terms of usability and operability. The application layer provides the GUI with the necessary software modules to achieve the intended functionality. These software modules communicate with the Android OS layer that serves as middleware between the hardware layer and application layer.

F. Graphic User Interface

The proposed graphic user interface was designed according to customer needs. The interface consists of a series of displays called activities. Each activity has a particular functionality and, in some cases, are related to each other in a hierarchical structure.

The GUI architecture, shown in Fig. 6, presents six activities: Splash activity, Main Menu activity, Bed Positions Menu activity, Alarm Menu activity, Monitoring activity and Configuration activity. The Splash activity described in the next section links directly to the Main Menu activity. The Main Menu has button options that link to each of remaining activities which are activated when the user clicks the corresponding button.

1) Splash: The Splash activity is designed as the entry point of the software. This activity is displayed immediately after the user starts the application and it displays a graphic for a short period of time (usually 3 seconds). The graphic of the Splash activity is usually the logo of a company or the name of the application. After the corresponding display time, the activity then transitions automatically to the Main Menu activity.

2) Main Menu: The Main Menu activity has a set of visual and functional components. Visual components correspond to the patient's brief information such as name, weight, age, and current prescription. On the other hand, visually functional components correspond to the buttons that link to sub-activities such as bed positions, alarms, bed and patient movement monitoring, and settings.

3) Bed Positions: The Bed Positions activity mainly consists of visually functional elements to control the physical SmartBed. When this activity is launched, it automatically checks whether successful Bluetooth connection has been established with the pre-defined hardware component of the SmartBed. In case Bluetooth connection has not been established, a pop-up notification is sent to the user to perform Bluetooth connectivity. When the user clicks a particular button, the angle data is sent to the SmartBed, but also is stored in the local database to be displayed by the monitoring activity and synced to the cloud server.

4) Alarms: The Alarms activity is designed to be used by the patient in order to express certain needs or feelings to the caregiver. When a particular button is clicked, a sound alarm will be activated. Each alarm may be configured to specific sounds in order to allow the caregiver to understand patient needs without having to go to the visually/verbally check the patient needs.

5) Monitoring: The Monitoring activity is divided into two panels: side menu and data display. In the side menu, patient's info is displayed along with two buttons: Bed Record and Patient Record. When Bed Record button is clicked, bed positions record is shown in the data display panel. The Bed Position Record corresponds to the list of positions (with their corresponding time-stamp) that the user has activated during certain time interval.

6) Configuration: The Configuration activity is also divided into two panels: Side Menu and Data Display. In the Side

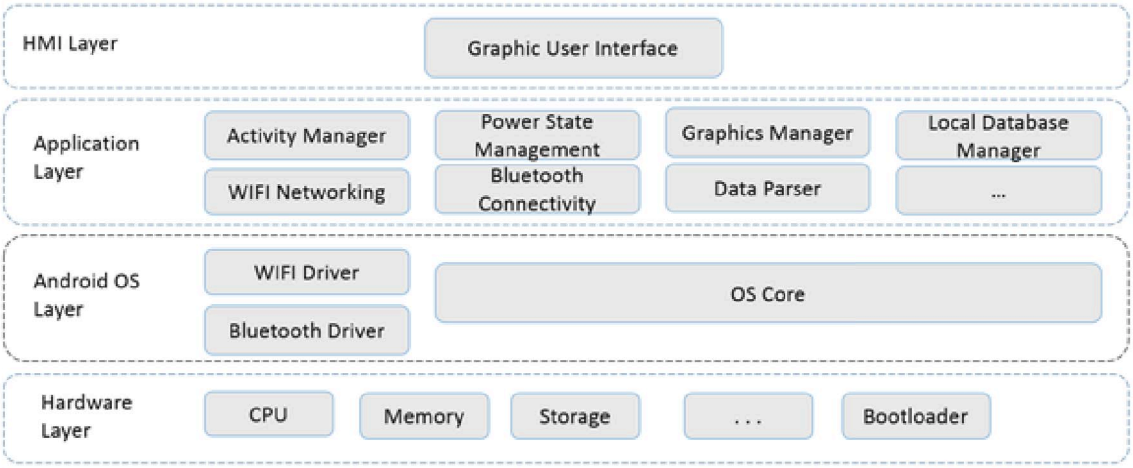


Fig. 5. Software Architecture: HMI Layer and Application Layer custom designed for Android Devices

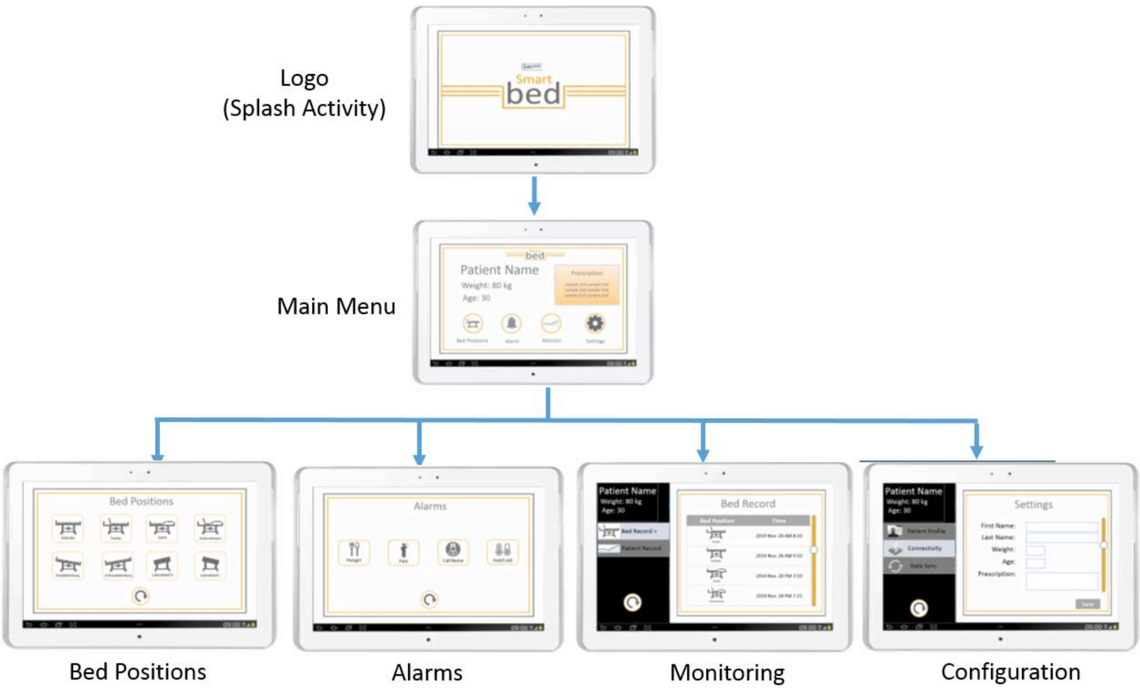


Fig. 6. Graphical User Interface Layout

Menu, patient's info is displayed along with several buttons corresponding to the settings configuration of the application, such as patient's profile, connectivity, or data synchronization. On the Data Display panel, the user can modify the settings for the particular option selected in the Side Menu. Settings changes will take effect immediately after the corresponding modification has been made by the user. Future settings options will be added to the interface as software updates are available.

III. User Study

A user study was conducted with two main objectives: 1) Confirm the functionality of the system, and 2) evaluate users' perception of the interface to control the bed. Twenty participants: 12 male, 8 female (ages M=25.3, STD=2.34) participated in the study that lasted approximately 10 minutes.

The user study consisted in the following:

- *Training (1 min)* - participants laid down on the bed and were given instruction on how to navigate the user interface.
- *Predefined sequence (2 mins)* - participants experienced the automatic movement of the bed that was preprogrammed with a predefined sequence of positions. (Fig. 7)
- *Free control (3 mins)* - participants freely selected bed positions.
- *Questionnaire (4 mins)* - participants filled out a questionnaire

A Godspeed style questionnaire [12] was used to evaluate

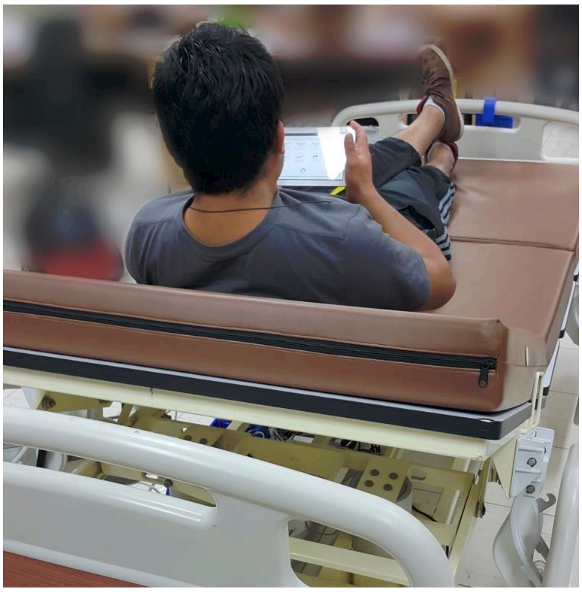


Fig. 7. Software During Testing

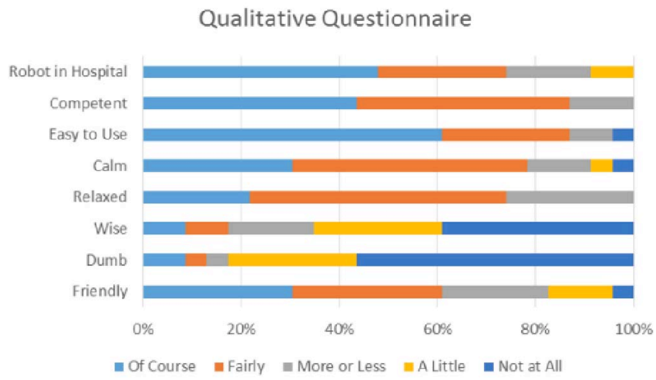


Fig. 8. Qualitative Questionnaire Results

user's perception of the system. It is important to mention that participants were instructed to consider the smart bed to be a friendly robot and evaluate it accordingly.

The questionnaire consists of few questions concerning the user's perception on how 1) Friendly, 2) Easy to use, 3) Competent, 4) Calm, 5) Relaxed, 6) Wise, 7) Dumb the system is. We added one more question on whether participants would prefer to have smart robotic beds in a hospital environment. The evaluation rating scale is as follows: 1) Strongly disagree, 2) disagree, 3) neither agree or disagree, 4) agree, 5) strongly agree.

IV. Results

Questionnaire results summarized in Fig. 8 indicate the 80% of participants agree the system is somewhat friendly and 83% agree it is quite easy to use. Moreover, 74% of participants felt relaxed and calm during the trial. Lastly, 74% of participants agree that they would like to have these type of bed systems in a hospital environment. Regarding system functionality, almost 90% of participants considered the system to be quite competent given that it responded to their control commands.

V. Conclusions and Future Work

The SmartBed has the characteristics of an Intelligent Mechatronic System that could provide rehabilitation and assistance services to people with disabilities. However, for the SmartBed to be a useful device, the technology developed must be of public acceptance. Moreover, it should aid in providing, if not the same, more sense of autonomy to the patient. This raises the question as to how autonomous this system should be and which end-user has more priority on its usage: the patient or the medical personnel.

At the time of publication of this paper, the mechatronic hospital bed is being tested within real hospital environments with test patients and caregivers. From the feedback acquired, the system will be validated, and the suggested improvements will be considered for the following design of the SmartBed.

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