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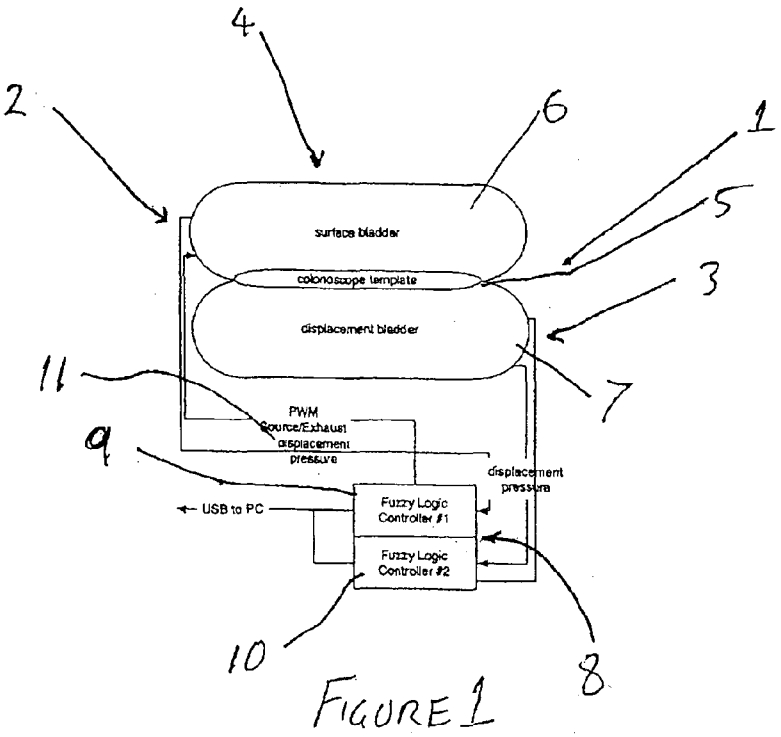

FIGURE 1

(57) Abstract: The present invention relates to a simulator apparatus for simulating a response to a tactile medical examination of a patient. First and second bladders, positioned in use on top of each other, are used to provide first and second tactile feedback arrangements, respectively. The bladders are controlled to simulate a patient surface tactical feedback, in order to facilitate training of operatives.

WO 2011/120094 A1

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A METHOD AND APPARATUS FOR SIMULATING A HAPTIC RESPONSE

FIELD OF THE INVENTION

The present invention relates to an apparatus and method for simulating a response to a tactile medical examination of a patient, and, particularly, but not exclusively, to a method and apparatus for simulating a response to a tactile medical examination of a patient's abdomen.

BACKGROUND OF THE INVENTION

Many medical procedures require a physical examination of a patient which may involve a haptic examination of the patient. For example palpation of the abdomen, or other parts of the body, in order to locate objects, organs, tissue masses, of the patient.

For example, medical procedures such as colonoscopy and endoscopy may often require haptic examination in order to ensure that the operation proceeds correctly. In a colonoscopy, for example, it may be necessary to locate the position of the colonoscope in order to ensure that the correct path is traversed. A common and important procedure in colonoscopy involves cooperation between the gastroenterologist and assistants in the application of abdominal palpation. Palpation techniques are used in 15 to 20% of cases to aid the gastroenterologist in navigating the colonoscope.

Palpations are conducted by an assistant (usually) using the fingers, palm or forearm over identified regions of the abdomen to increase the rigidity of the nearby colon segments, thereby suppressing loop formation and enabling tip (colonoscope tip) navigation past troublesome

flexures. A problem is that novice gastroenterology assistants commonly perform their first abdominal palpation on a colonoscopy patient without any tactile foreknowledge of magnitude, direction and effective abdominal pressure. Commercially available colonoscopy simulators focus generally on solely training the gastroenterologist to navigate the colon and neglect the equally important cohesive team skills for all people participating in the procedure. There are no suitable simulators available to train gastroenterology assistants.

The abdomen is a complex combination of various soft-tissue organs and tissues such as fat, muscle, liver, large and small colon. The make up of these soft tissues and their anatomical layout contributes to the tactile feedback during the palpation and thus are important factors to consider in abdominal simulation.

SUMMARY OF THE INVENTION

In accordance with a first aspect, the present invention provides a simulator apparatus for simulating a response to a tactile medical examination of a patient, comprising a first tactile feedback arrangement and a second tactile feedback arrangement, the first and second tactile feedback arrangement being arranged together to provide a response simulating patient surface tactile feedback and a patient body type.

In an embodiment, the first and second tactile feedback arrangements are arranged to operate together to provide response components giving a total response which comprises the surface tactile feedback component and the tactile response representing a varying patient body type. In an embodiment, the first tactile feedback arrangement is a first fluid operated bladder arranged to provide a

variable pressure response to tactile stimulation.

In an embodiment, where the first tactile feedback arrangement is a first fluid operated bladder, the second tactile feedback arrangement comprises a platform body arranged, in operation to support the first fluid operated bladder. In an embodiment, the platform body is arranged to vary in height relative to the first fluid operated bladder. In an embodiment, the platform body is arranged to control displacement of an interface with the first fluid operated bladder. The height of the interface can be varied. This facilitates simulation of patient body type. In an embodiment, the body type may be related to virtual Body Mass Index (BMI) of the simulated patient. In an embodiment, the first fluid operated bladder is constrained with the platform in a preset volume. In an embodiment, the preset volume constraint is implemented by an enclosure mounted about the fluid operated bladder and the platform. The enclosure may comprise webbing

In an embodiment, the second tactile feedback arrangement comprises a second fluid operated bladder.

In an embodiment, utilizing a plurality of fluid operated bladders to provide tactile feedback in a haptic operation, has the advantage that it provides a relatively realistic response.

In an embodiment, a fuzzy logic control system together with a plurality of valves is used to vary fluid pressure within the first and second bladders.

In an embodiment, the apparatus further comprises a probe body, arranged to represent a moveable probe within a patient. For example, the probe body may represent a colonoscope, so that a colonoscopy operation can be simulated via the apparatus. In an embodiment, the probe

may be positioned between the first and second tactile feedback arrangements. Where they are first and second bladders, the probe's motion is determined at the interface between the bladders.

An advantage of such a simulator apparatus, in at least an embodiment, is that the simulator is available to enable doctors and their assistants to simulate haptic operations on patients.

A further advantage of at least an embodiment of the present invention is that the apparatus is able to be implemented in a mannequin, providing a fully immersive solution, to enable comprehensive training of operators.

In an embodiment, a plurality of simulator apparatus may be used together to provide a system for representing a part of a patient's body, such as the total abdominal or chest area. For example, a plurality of the apparatus may be used in different locations eg in a mannequin, to represent the "feel" of various parts of the abdomen and/or chest and/or other parts of the body in haptic operations.

In accordance with a second aspect, the present invention provides a simulator apparatus for simulating a response to a tactile medical examination of a patient, comprising a first tactile feedback arrangement and a second tactile feedback arrangement, the first tactile feedback arrangement comprising a body arranged to provide a tactile response to manipulation of the body by an operative, and a second tactile feedback arrangement comprising a further body forming an interface with the first tactile feedback arrangement, and being operable to raise or lower the interface to bring the interface into or out of haptic range of the first tactile feedback arrangement.

In an embodiment, objects may be supported at the interface, and when the interface is within haptic range, the objects may form part of the tactile feedback response provided to the operative.

In an embodiment, the system further comprises a probe body positioned at the interface. The probe body may represent a simulated colonoscope.

The first tactile feedback arrangement body may comprise a fluid operated bladder. The further body may comprise a fluid operated bladder.

This aspect of the invention may have any or all of the features of the first aspect of the invention.

In accordance with a third aspect, the present invention provides a simulator apparatus for simulating a response to a tactile medical examination of a patient, comprising a first fluid operated bladder and a second fluid operated bladder, wherein the first fluid operated bladder is positioned, in operation, on top of the second fluid operated bladder.

This aspect of the invention may have any or all of the features of the aspects of the invention discussed above.

In accordance with a fourth aspect, the present invention provides a simulator system, comprising a plurality of stimulator apparatus in accordance with any of the first to third aspects of the invention, positioned with respect to each other to represent a part of a patient's body for simulating a response to a tactile medical examination of the part of the patient's body.

In an embodiment, the part of the patient's body may be

the abdomen. In an embodiment, the portion of the patient's body may be the chest.

In an embodiment, the system may form part of a mannequin, or may be positioned within a mannequin.

In accordance with a fifth aspect, the present invention provides a mannequin, representing a patient body, and comprising a system in accordance with the fourth aspect of the invention.

In accordance with a sixth aspect, the present invention provides a method of simulating a response to a tactile medical examination of a patient, comprising the steps of providing a tactile feedback response, simulating patient surface tactile feedback and a patient body type.

BRIEF DESCRIPTION OF DRAWINGS

Features and advantages of the present invention will become apparent from the following description of embodiments thereof, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 is a diagram of a simulator apparatus for simulating a response to a tactile medical examination of a patient, in accordance with an embodiment of the present invention;

Figure 2 is a diagram of a first and second fluid operated bladder of the apparatus of Figure 1;

Figure 3 is a diagram of a first bladder of Figure 1, illustrating part of a control arrangement;

Figure 4 is a schematic diagram illustrating a control

arrangement for a single bladder of an apparatus in accordance with an embodiment of the present invention;

Figure 5 is a flow chart illustrating processing of user interactions with an apparatus in accordance with an embodiment of the present invention;

Figure 6 and Figure 7 are diagrams of a first and second bladder arrangement of the apparatus of the embodiment of Figure 1, illustrating an operation of the apparatus;

Figure 8 is a diagram illustrating how a system in accordance with an embodiment of the present invention may be deployed in a mannequin; and

Figure 9 is a diagram of the embodiment of Figure 1 showing the arrangement as seen from above.

DETAILED DESCRIPTION OF EMBODIMENTS

Referring to Figure 1, a simulator apparatus in accordance with an embodiment of the invention, generally designated by reference numeral 1, comprises a first tactile feedback arrangement 2 and a second tactile feedback arrangement 3. The simulator apparatus 1 is arranged to simulate a response to a tactile medical examination of a patient. A trainee operative can carry out haptic operations on the first and second tactile feedback arrangements, usually from the top surface 4, and obtain a response which simulates a corresponding haptic operation on a real patient. In an embodiment, the response can simulate a patient body type, for example as represented by BMI.

As discussed above, the abdomen is a complex combination of various soft tissue organs and tissues. Further, the tissue mass and density of human patients varies greatly.

This variation can be represented by the body mass index (BMI). In this embodiment, the first feedback arrangement 2 is arranged to provide a haptic response which represents the tactile feedback of the surface of the patient, and the second feedback arrangement is arranged to be controlled to raise or lower an interface between the second tactile feedback arrangement and the first tactile feedback arrangement. Raising or lowering of the interface brings the interface into or out of a haptic range of the first feedback arrangement. An object supported by the interface may therefore form part of the tactile response to a greater or lesser extent, depending upon the level of the interface.

In more detail, this embodiment of the invention is implemented as a haptic simulator for simulating colonoscopy operations. As well as the first 2 and second 3 feedback arrangements, the apparatus comprises a probe body 5. The probe body 5 in this embodiment represents a colonoscope 5, and can be moved to provide a simulation of the "feel" of a colonoscope when the operative palpates the surface 4.

Each of the first and second feedback arrangements comprises a respective first 6 and second 7 pneumatically operated fluid filled (in this example the fluid is air) bladder. The colonoscope template 5 is interposed at the interface between the first 6 and second 7 bladder. A substantially fixed volume mesh 8 encloses the bladders 6 and 7, in order to control the overall volume.

Pressure within the bladders 6 and 7 is controlled by a fuzzy control system 8 controlling a plurality of valves (not shown in Figure 1, to be described later) for sourcing and exhausting air to/from the bladders 6 and 7.

The fuzzy control system 8, as illustrated in Figure 1,

comprises a first fuzzy logic controller 9, responsible for control of pressure in the first bladder 6 and a second fuzzy logic controller 10 responsible for control of pressure in the second bladder 7. Fuzzy logic controller 9 and fuzzy logic controller 10 are connected in turn via a USB port to a computing device such as a PC (not shown). The fuzzy control system is coupled with a pulse width modulation scheme to maintain the pressure/vary the pressure given a control input (reference numeral 11).

The applicants have realized that there are two main components of haptic feedback during a colonoscopy procedure. Firstly, the forces felt at the operative's hand (fingers or palm). The amount of force applied depends greatly on different body types, primarily the abdominal fat and muscle content. Secondly the body type will determine if the operative can feel the colonoscope during the application of abdominal pressure. As such, the direction and amount of pressure is applied on a trial and error basis to regulate paradoxical motion (of the colonoscope).

In this embodiment, the first (surface) bladder 6 is used to simulate the forces during abdominal palpation as experienced by the palm of the operative's hand or fingers. The forces change in a non-linear fashion over the interaction depending on the depth of the interaction and the biomechanical properties of the patient's abdomen.

The second (displacement) bladder 7 is used to control the height of the colonoscope template 5, as measured from the base of the apparatus. Depending on the patient, the colon may be unobstructed to fat and muscular tissue (such as elderly women, for example). That is, there is a relatively low BMI. Whilst in obese patients the converse may be true and it may not be possible to feel the

colonoscope. The colonoscope height can therefore be predetermined and set for the simulation, via the displacement bladder 7. In an embodiment, dynamic height control during interaction by varying the pressure in the displacement bladder 7 may also be implemented.

The applicants have found that using a plurality of bladders in this way, a surface bladder providing haptic feedback, and a lower, displacement bladder raising or lowering an interface, is an advantageous and effective way of simulating response to a tactile medical examination of a patient.

Figure 3 is a diagram of the surface bladder 6 showing the arrangement in more detail. A PWM (Pulse Width Modulated) signal controls source and exhaust via intake valves 15 and 16. Pressure sensors 17 are able to sense pressure within the bladder 6.

The fuzzy logic is used to control a specific bladder property in response to a user determined variable eg pressure or displacement. Fuzzy control operation details are documented in a paper "Pneumatic Haptic Interface Fuzzy Controller for Simulation of Abdominal Palpations During Colonoscopy" proceedings of the third joint Euro-Haptic Conference and Symposium on haptic interfaces for virtual environment and teleoperator systems, IEEE press (2009), 250-255. This paper discloses only a single bladder and a single bladder control system. A description of the single bladder control system is given later on in this description under the heading "Single Bladder Control System".

A more detailed diagram of the control system for a single bladder, in this case the surface bladder 6, is shown in Figure 4. Four pressure sensors 17 are distributed within the bladder. Pneumatic actuators are used in the form of

fast switching solenoid valves from Matrix. They have fast operating speed and low cost relative to proportional controllers. Solenoid valves (model 820NC2/2) were used with a speed up circuit achieving an on/off frequency of 500 hertz. One solenoid valve 15 is connected to the bladder and supply pressure and used to modulate the inflation rate (valve 15). The other solenoid valve is used to modulate the deflation rate (valve 16). PWM is implemented as a modified pressurized linear modulation scheme as described in the paper by Van Varseveld et al (R.van Varseveld and G. Bone. "Accurate position control of a pneumatic actuator using on/off solenoid valves". *Mechatronics, IEEE/ASME Transactions on*, 2(3):195-204, 1997). This paper is also incorporated herein by reference.

The bladders may be of any convenient material, but in this embodiment, the bladders 6 and 7 are of rubber in order to allow the operative to interact in natural manner akin to the feel and flexibility of human tissue during palpation. The bladders are 9cm by 11cm two-valve sphyganometer bladders.

The two bladder control systems of this embodiment of the present invention is illustrated in Figure 1. Two control systems such as illustrated in Figure 4 may be utilized.

The displacement bladder 7 is arranged to bring the colonoscope template 5 into interaction range when necessary (static implementation) or appropriate (dynamic implementation using simulation models). The height of the bladder is controlled by a similar fuzzy control system to the surface bladder, using the bladder height as the fuzzy control variable.

In this sense, the two control systems operate in parallel but are decoupled. However, more complex fuzzy control can

be implemented to offer improved control of the bladder dynamics.

The simulation software and physical modelling will determine the patient property for simulation and the desired pressure feedback and height of colonoscope will be calculated and simulated by the haptic device.

The use of the multi-bladder haptic device is created to simulate the tactile simulation of abdominal palpations for varying body types experienced in every day procedures. To provide haptic simulation, the system must react to user interactions and adjust the simulation accordingly. This process is illustrated in Figure 5.

The fuzzy control system will treat the user interaction as a disturbance and attempt to correct to retain the target pressure. The changes in palpation depth will be communicated to the PC over the USB connection where a new target pressure will be calculated. The fuzzy control system will correspondingly control the pressure to the target pressure, thereby simulating the tactile feedback for the compression of abdominal tissue.

The user interaction will also lead to a change in displacement in the displacement bladder. As such, the fuzzy logic control responsible will increase in the lower bladder pressure to maintain the height of the colonoscope template. In this manner the two separate fuzzy logic controllers maintain the balance of forces, which will drive the simulation from initial to full palpation depth; the depth at which the interaction point contacts the

bottom of the bladder and the underlying colonoscope template.

In the case of a relatively slim patient, the lower bladder will be almost at full extension bringing the colonoscope template very close to the surface of the haptic device, thereby simulating colonoscope interaction (Figure 6). As the operative applies the initial pressure to the haptic device the immediate pressure of the top bladder will increase resulting in the bottom layer deforming. The process as depicted in Figure 5 will communicate changes to the PC simulation models where new target values will be determined. One can assume in the low BMI case the target pressure will increase rapidly in comparison to change in displacement.

In a relatively larger patient the lower bladder is depressurised to maintain a low displacement allowing a large amount of palpation depth in the surface bladder (Figure 7). In this simulation it may be desirable to limit or even prevent the operative's palpation from interacting with the colonoscope. This is accomplished by rapidly increasing the surface bladder pressure once the maximum palpation depth, as determined by PC driven simulation, is reached.

Highlighting the two extremes of BMI is to illustrate that the regular patient will be a blend between these two extremes. The palpation depth and depth of the colonoscope template will depend on the virtual patient which is being simulated on the host PC.

The displacement bladder 7 is a dynamic system, which will react to target distance as determined by simulation models on the PC. The virtual patient is likely to have a static target distance per region.

The dynamics as described above is a simple interaction between the surface and underlying bladder with minimal sharing of information between the two fuzzy control systems. The hardware control is designed to accommodate more intelligent control systems involving more complex dynamics, which will take full advantage of the bladder dynamics.

Figure 9 shows a view of the bladder arrangement from the top. In this view, the colonoscope template 5 is shown in a bent configuration (in ghost outline).

The above embodiment shows a single apparatus which may provide haptic feedback. To provide a totally immersive system, a plurality of such apparatus may be used together. Figure 8 illustrates an embodiment of the invention which uses a plurality of the apparatus of Figure 1, within a mannequin. Each of the apparatus are designated by reference numeral 1 in Figure 8, to indicate that they are the same type of apparatus. In the embodiment of Figure 8, there are four apparatus distributed to represent parts of the abdomen critical for colonoscopy operations. This provides an immersive simulation environment for a colonoscopy operation.

A flexible sensor skin is envisaged for the surface of the mannequin to determine the site of user interaction and used as input to simulation models. Position information

can then be added to the haptic response to provide further detail for the simulation.

The apparatus of the present invention could be utilised to represent other parts of the body, eg chest, leg, etc where it is necessary to simulate a palpation operation. One, two or more of the apparatus may be used to provide the appropriate "virtual" body layout.

In the above embodiment, a dual-bladder system is disclosed. The invention is not limited to this. In some cases, a multiple bladder system, of three or more bladders that are used together in an apparatus, may provide the appropriate haptic response.

In the above embodiment, two pneumatic bladders are used. In an alternative embodiment one pneumatic bladder may be used as the surface bladder, and in order to provide displacement for the colonoscope, a platform (ie not a bladder) that can be raised or lowered may be used instead of a bladder.

In the above embodiment, the bladders are pneumatic (air operated) bladders. The invention is not limited to pneumatic operated bladders. Any fluid may be utilised if it gives the right haptic response. For example, in some cases, a liquid filled bladder may be used eg hydro. Other gases may be used than air if they provide the appropriate response.

In the above embodiment, two bladders are controlled by separate fuzzy logic systems. The invention is not

limited to this. The control system may share information from the feedback systems.

In the above embodiment, the bladders are on top of each other. The invention is not limited to this. In other embodiments, it may be appropriate to have bladders side by side providing different response characteristics, for example, or in other spatial arrangements with respect to each other.

In the above embodiments the application is for a human patient. The invention is not limited to this, application may simulate haptic operations in animal patients.

In the above embodiment, the apparatus has a probe body positioned between the bladders. This simulates a colonoscope operation. The present invention is not limited to simulating a colonoscope operation. Other probes (eg endoscope) may be represented. There may also be embodiments where no probe is included. For example, where it may be necessary for training to feel types of organs or condition of organs. For example, an object representing a tumour or other condition may be provided at the interface.

Body Mass Index (BMI) is one indicator only of varying body type. The invention is not limited to operating based on BMI, but may include other factors or alternative factors in the simulation for providing an appropriate haptic response.

Embodiments of this invention may be used in any haptic training, including abdominal palpation, midwifery and others.

It will be appreciated by persons skilled in the art that numerous variations and/or modifications may be made to the invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects as illustrative and not restrictive.

The following disclosure is a description of the single bladder control system disclosed in the paper referred to on page 10 of this specification, "Pneumatic Haptic Interface Fuzzy Controller for Simulation of Abdominal Palpations During Colonoscopy".

APPENDIX

SINGLE BLADDER CONTROL SYSTEM

Pneumatic control has been used for armature control of robots with pneumatic air muscles achieving accurate position control of the piston actuator with inexpensive solenoid valves. We describe a pneumatic fuzzy controller associated with a pulse width modulation conversion scheme in a novel haptic device within a colonoscopy simulation system. A rubber bladder was used to simulate forces experienced during abdominal palpation during colonoscopy. The haptic device showed good steady-state response when tested with step inputs. A settling time of 0.41s was achieved on positive control step and 0.52-0.81s for negative steps. Dynamic response was adequate for mimicking interactions during inflation stages while noticeably deficient during deflation periods. Tracking accuracy averaged 94.2% within 300ms of the reference input while the user was actively applying abdominal palpation and minor repositioning.

KEYWORDS: Tactile devices and display, Human-computer interaction, Dynamic systems and control.

INDEX TERMS: H.5,2 [Information Interfaces and Presentation]: User Interfaces-Theory and methods; J.7 [Computers in Other Systems]; Process Control C.3 [Special-Purpose and Application-based Systems]; Process control systems.

1. Introduction

Colonoscopy simulators have been used increasingly in colonoscopy training to reduce training time, financial and opportunity costs. Simulators can provide procedure specific metrics, repeatability of different cases, and decreased cost for colonoscopy training. Furthermore, they may facilitate gastroenterology curricula by providing a more systematic and documented approach.

A common and important procedure involving cooperation between the gastroenterologist and assistants is the application of abdominal palpation during colonoscopy intervention. This is done by one of the assistants to aid navigation past certain flexures by applying hand pressure at specific locations on the abdomen. However, all commercially available simulators aim at training the gastroenterologist alone rather than a simulation environment for the entire colonoscopy team. Palpation techniques are used in 15-20% of cases to aid the gastroenterologist in navigating the colonoscope [8]. A haptic device used to simulate such procedures would be highly desirable as it would improve intra-team communication and cooperation skills. However, to our knowledge no such device exists.

Our goal is to build a realistic haptic device using a mannequin for use in colonoscopy simulation using pneumatic actuators simulating abdominal forces. In this paper, we present a control strategy to regulate air pressure in a sphyganometer bladder with enough bandwidth to follow actual forces recorded during interventions.

We first discussed related works in Section 2, followed by the description of hardware design and the mathematical modelling of the air bladder in Section 3. The control output design for the control scheme of pulse width modulation (PWM) is described in Section 4, followed by the fuzzy control design in Section 5. Experimental results are reported in Section 6, before concluding.

2. Related Works

During colonoscopy procedures, colonoscope loops and patient anatomy might impede insertion. In these cases, the gastroenterologist identifies the likely location of the impedance and asks for an abdominal palpation to be performed by one assistant. However, the gastroenterologist can only estimate the location of the colonoscope or loop due to limited information. As such, constant communication is needed between the two specialists to locate where and how much pressure would be most effective. Once this area is determined, the palpation proceeds, trading off effectiveness against patient discomfort [8].

Prechel et al [8] described four main palpation areas (Figure 1a); the sigmoid lift, the sigmoid/transverse colon, the sigmoid hepatic flexure, and the cecal lift. An example of the sigmoid/transverse palpation technique is shown in Figure 1b.

Pneumatic actuators have been used instead of servo-electrical motors and piezoelectric in some robotic applications due to their light weight, high power to weight ratio, low cost and ease of maintenance. As such

they have been implemented in robotics as air muscles, piston control or haptic gloves.

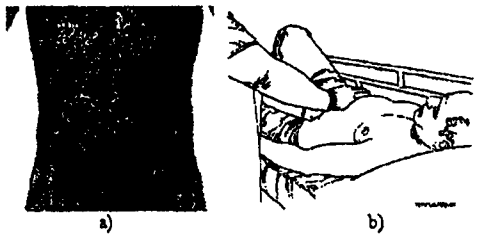

Figure 1: (a) Abdominal pressure is applied in these four regions to aid navigation of the colonoscope;
(b) Pressure applied on the sigmoid/transverse colon [8].

However, pneumatic system have a number of non-linearities, challenging control systems to achieve accurate and fast regulations. These include the air compressibility, high friction, deadband due to stiction, and non-linear flow rates due to tube geometry and valves. Without comprehensive mathematical modelling, traditional linear control methods typically have limited static and dynamic performances.

Studies have shown that using pneumatic air muscles, pressure could be controlled within a constricted air bladder and converted into lateral forces [11, 4]. Pneumatic air muscles have also been used in robotic arms where solenoid valves controlled armatures up to 30° with a setting time less than 0.3ms with limited oscillation during steady-state [12]. Some researchers reported good steady-state control accuracy using low cost on/off solenoid valves [13, 6], but they have been seldom used for pneumatic control as they introduced non-linearities from limited solenoid flow rates, low valve response time, and high noise levels due to rapid PWM. A number of

control algorithms have been designed to compensate for these issues, such as complex proportional-integral-derivative (PID) control [13, 11], sliding order control [9, 7] or fuzzy control [10]. This has resulted in improved dynamic response of the piston despite low resolution actuators [14].

Fuzzy control largely followed one of two methodologies. Firstly, fuzzy control served as a supervisory system on top of an existing controller to adjust the gain of coefficients based on inputs [3]. Gao et al described a Fuzzy-PD controller with settling times ranging from 0.5 to 1 second to regulate piston position with a stroke in the range of 20mm-800mm [3]. The relatively slow dynamic response of these systems was attributed to the fuzzy gain control not accounting for the pneumatics non-linearities. Secondly, fuzzy control has also been implemented as part of a negative feedback loop instead of a linear PID controller [6, 14]. Hybrid controllers have been described using a macro (fast) and micro (fine) control schemes. Parnichkun et al [6] used fuzzy control on a macro level and employed PID for improved accuracy which had a slightly faster performance than a traditional PID approach. Ying et al [14] used fuzzy control for fine regulation whereas a bang-bang controller regulated large displacements. However, they reported oscillation in both step and sinusoidal responses despite a fast settling time of 20ms. Alternatively, Shih et al. [10] proposed an all fuzzy approach to control the position of a pneumatic cylinder with an error of less then 0.1mm under loaded or no load conditions with a settling time of 0.5s despite relatively older solenoid valve technology. Despite the use of on/off solenoid valves, fuzzy control systems have

been able to account for pneumatic non-linearities with low steady-state error and good dynamic response.

For our application, we have combined the system design of air muscles with an accurate controller derived from pneumatic piston control. We have addressed non-linearty issues by using an all fuzzy control. We now describe our system.

3. System Description

We designed our haptic system to be able to sense forces from a user's manual interaction and provide them with force feedbacks using an air bladder. We formulated a mathematical model to convert force in newtons (N) to pressure reference (kPa) which was used by the fuzzy controller.

3.1 Hardware Design

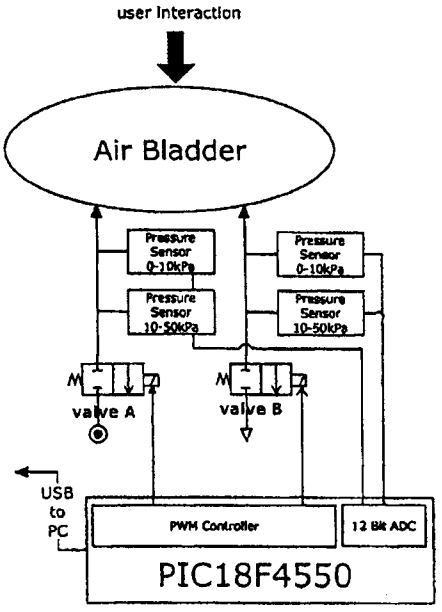

Figure 2: Hardware Diagram of Pneumatic haptic System

The hardware design of the pneumatic haptic device is shown in Figure 2.

When conducting an abdominal palpation, the gastroenterology assistant interacts with the patient by placing his/her hands on the abdomen and gradually applies force to gently move the colon and colonoscope. During a palpation, force feedback is initially minimal due to the subcutaneous fat and the initial elasticity of skin. But as the palpation depth increases, the resistance felt by the assistant increases as organs and muscle tissues are compressed. Other environmental factors, such as the presence of the colonoscope in the palpation area, or the respiration might also influence the resistive force. To simulate this behaviour, a 9cm by 11cm two-valve sphyganometer bladder was used to convert pneumatic pressure into resistive force feedback. The rubberised bladder, originally used for blood pressure measurements, allowed the chamber to simulate the feel and flexibility of human tissue during palpation illustrated in Figure 1b. A photograph of the air bladder is shown in Figure 3.

Figure 3: 9cm by 11cm 2 valve sphyganometer bladder

The rubberised surface of the sphyganometer could resist to stretching or distension up to 5kPa of pressure. Large distension would cause an unnatural lump on the mannequin surface and detract from realism. The change in volume could cause a decrease in pressure within the bladder and thus would decrease the responsiveness of control. To avoid those issues, the air bladder was placed into a cloth mesh pre-empting large unnatural distensions.

The pneumatic actuators used were fast-switching solenoid valves from Matrix [2]. They were chosen for their fast operating speed and low cost relative to proportional controllers. Solenoid valves (model 820 NC 2/2) were used with a speed up circuit achieving an on/off frequency of 500Hz. One solenoid valve was connected to the bladder and supply pressure and used to modulate the inflation flow rate (valve A). Likewise, the other solenoid valve was used to modulate the deflation rate (valve B).

Sensors were attached after each valve and used as inputs to the feedback control loop. Freescale MPXV5010G integrated pressure sensors were used to cover the 0-10kPa range while MPX5050G sensors were used to cover the 10-50kPa range [1]. The operating range was between 0-8kPa.

These sensors were sampled by a 12-bit ADC equipped microprocessor (Microchip, PIC18F4550) at 1 kHz and streamed back to the PC over a USB interface. The readings from the sensors were processed to determine the bladder pressure whilst filtering for noise due to the sensor and the PWM control. The reference forces were transferred back through the USB interface to the fuzzy controller.

3.2 Bladder Force Model

The purpose of the air bladder was to provide force feedback to the user by controlling the pneumatic pressure within the bladder. As the user interacted with the bladder, the resistive force F was sent a reference force to the controller, which converted it to a pressure reference. We assumed that:

- air is an ideal gas
- pressure and temperature of the air is homogeneous within the bladder

The pressure required to generate a normal force on the surface the bladder was estimated by $F=P/A$, where F was the reference normal force in N, A the area of interaction in m^2, and P the pressure in kPa. We assumed the contact area to be constant and equal to that of a typical hand application of 7cm by 9cm. The reference pressure was therefore proportional to the reference force as determined by data or physical model.

4. PWM Control Output Design

PWM converted the controller output command, u, ranging from -100% (full deflation) to 100% (full inflation), and was converted to duty cycle values for both valve A and B to regulate the flow rate. Linear PWM conversion schemes have been used commonly in pneumatics, and typically $u = 0$ when valves A and B were closed [13]. When the command u was positive, only valve A was activated; and only valve B, for negative u. This control scheme however introduced

a deadband in the flow rate in cases where *u* was almost zero. This was due to the valves being activated with a duty cycle shorter than the time required to open and close the solenoids. We designed a system to avoid deadband as it could result in steady-state error, overshoots and oscillation in pressure control.

Van Varseveld et al [13] suggested several PWM conversion alternatives to overcome the deadband and linearise flow rate relative to control output. We modified one of those techniques, namely the pressurised linear control scheme. It was able to overcome deadband issue but suffered from low flow rate [5, 13].

Pressurised linear control differs to linear control scheme, when $u = 0$, both valves A and B were at maximum activation [13]. When *u* was positive, the duty cycle of exhaust valve B was scaled from 100 to 0 for $u = 100$, and conversely for supply valve. A when *u* was negative. This scheme is illustrated in Figure 4 where the conversion scheme for valve A and B is depicted in dotted line and solid line, respectively.

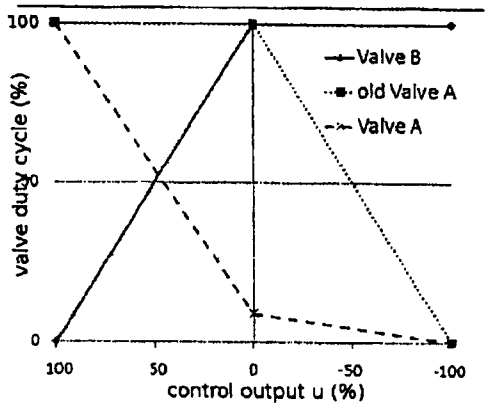

Figure 4: Pressurised Linear PWM (in solid and dotted Line) and the modified control scheme (solid and dashed line)

This implementation assumed that the inflation and deflation rate were equal which resulted in a net zero flow rate at $u = 0$. However, in our application, there was a large difference between deflation and inflation rate due to the large differential of chamber pressure to atmospheric or supply pressure [5]. For pressurised linear control, the control scheme was modified by reducing the duty cycle of valve A to maintain the net flow rate of zero at $u = 0$ and chamber pressure at 0kPa. The altered control scheme for Valve A is shown as a dashed line in Figure 4.

In our application, increased chamber pressure resulted in a change in flow rate for both deflation and inflation causing a risk of overshoot and oscillation. As the pressure increased, the command $u = 0$ resulted in deflation of the bladder. As a result, a higher duty cycle was needed on supply valve A to maintain zero flow rate at $u = 0$. To address this issue, the control scheme was modified to be pressure dependant by adjusting the duty cycle of valve A relative to the measured bladder pressure. The duty cycle of valve A which would generate a zero net flow rate was recorded for chamber pressure between 0-8kPa, at multiple 0.5kPa increment. This data was used to generate the control surface illustrated in Figure 5. Given the current chamber pressure, the valve A duty cycle could be interpolated for any value of u.

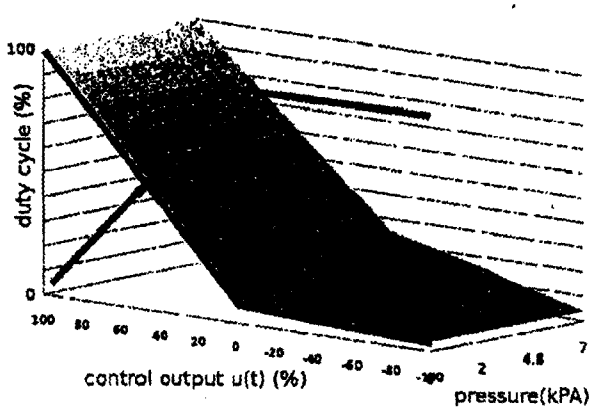

Figure 6: Flow rate over different chamber pressure. The surface shows the valve duty cycle for valve A for any given u or chamber pressure. Control scheme for valve B is shown in grey and is not pressure-variant.

5. Fuzzy Control Design

The many non-linearities associated with pneumatic systems impeded the development of a comprehensive mathematical model which sufficiently linearised or described the plant system.

It is well known that in those cases, control methods, such as PID and sliding control method may under-perform in terms of dynamic performance. Fuzzy control is a simple control method which allows for quick development of non-linear control without the need for a comprehensive mathematical description. It comprises of 3 main components: fuzzification inference, a knowledge base for determining output membership and defuzzification process to resolve output memberships to a scalar control output.

The fuzzy inference was described using linguistic variables as depicted in Figure 6-8. The input linguistic variables used were error $e(t)$ and change in error $\Delta e(t)$, expressed by

$$e(kT) = r(kT) - p(kT) \quad (2)$$

$$\Delta e(kT) = \frac{e(kT) - e((k-1)T)}{T} \quad (3)$$

where k was the total number of samples, T was the sampling time, $r(kT)$ represented the reference pressure, and $p(kT)$ was the current pressure value.

Asymmetric triangular fuzzy sets were used to describe the linguistic variables: eleven for the fuzzification of $e(t)$, seven for $\Delta e(t)$, and eleven for the $\hat{u}(t)$.

The linguistic labels used to describe the fuzzy sets were (N) negative, (NB) negative big, (NM) negative medium, (NS) negative small, (NV) negative very small, (Z) zero. Similarly, linguistic labels with P prefix were positive. The knowledge base consisted of 77 rules and is presented in a rule matrix as shown in Table 1.

$$E \in \{N, NB, NM, NS, NV, Z, PV, PS, PM, PB, P\},$$
$$\Delta E \in \{NB, NM, NS, Z, PS, PM, PB\},$$
$$U \in \{N, NB, NM, NS, NV, Z, PV, PS, PM, PB, P\}$$

The membership density of $e(t)$ was increased around zero, to facilitate a more precise control around the reference pressure whilst avoiding any oscillation or overshoot. Otherwise, the $e(t)$ memberships were spaced sparsely to encourage aggressive output control.

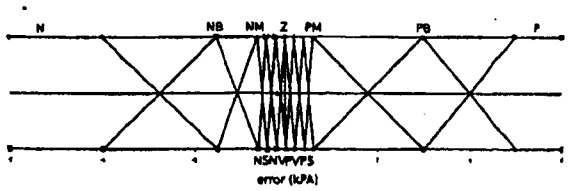

Figure 5: *e(t)* Membership function

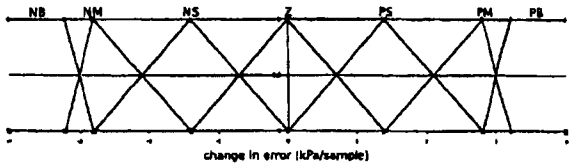

Figure 7: $\Delta e(t)$ membership function

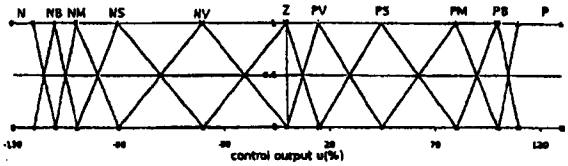

Figure 8: *û(t)* Output membership

The output linguistic variable $\hat{u}(t)$ was applied over the control response range -100% (full deflation) to 100% (full inflation) flow rate. Fuzzy sets N and P were saturated to 100 to translate control output at maximum activation. The output membership distribution (Figure 8) was heavily weighted for the negative output due to the large difference in exhaust and supply flow rates. The output distribution values were tuned to minimise oscillation and overshoot, whilst providing fast dynamic response for $e(t)$ and $\Delta e(t)$ values fuzzy sets.

Defuzzification used the centre of gravity method (COG) on the output fuzzy set to determine the control response u.

$$u = \sum_{U_{min}}^{U_{max}} \hat{u}.A(\hat{u}) / \sum_{U_{min}}^{U_{max}} A(\hat{u}) \qquad (4)$$

where $\hat{u}$ represented the mean of the active fuzzy set resulting from the rules matrix, $A(\hat{u})$ was the area determined by Mamdani interface, and u was the input to

the PWM control scheme as outlined in Section 4 to determine the duty cycle for each valve.

6. Results

Several experiments were conducted on the device to determine the performance of the haptic interface. We applied step and sinusoidal inputs to determine the static and dynamic response. In a third experiment, forces gathered during actual human palpation were used as reference force inputs. The resistive force generated by the bladder was measured using a force transducer fixed at 2cm penetration depth indicative of a mild palpation.

		$\Delta e(t)$						
		NB	NM	NS	Z	PS	PM	PB
	P	PM	PM	PM	PB	PB	P	P
	PB	PS	PM	PM	PM	PB	PB	P
	PM	PS	PV	PS	PM	PM	PB	PB
	PS	PV	PV	PV	PS	PM	PM	PB
	PV	NV	PV	Z	PV	PS	PS	PM
$e(t)$	Z	NS	NV	Z	Z	Z	PV	PS
	NV	NM	NS	NS	NV	Z	NV	PV
	NS	NB	NM	NM	NS	NV	NV	NV
	NM	NB	NB	NM	NM	NS	NV	NS
	NB	N	NB	NB	NM	NM	NS	NS
	N	N	N	NB	NB	NM	NM	NM

Table 1 Rule Matrix for inputs $e(t)$ and $\Delta e(t)$

Figure 9 shows the haptic device undergoing a set of step inputs illustrating the steady state response. The set-points were set at 39N and 85N which represented a small to medium palpation exerted on the bladder. In both cases, the fuzzy controller control output approached 100% between 80-94% of the settling time, and rapidly decreased for small error. Positive step responses showed an average settling time of 0.43s. The negative step response from 85N to 39N had an average settling time of 0.52s. However, in the case of the 39N to 0N step the average

settling time was 0.815s, almost twice as slow as a positive step response of the same size.

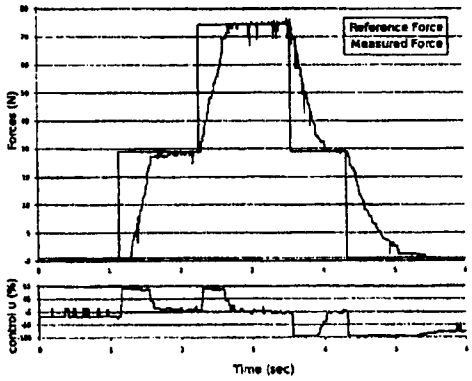

Figure 9: Step response of the haptic device over 6 seconds. The control output u is shown below the main graph.

The sinusoidal test used a sine wave ranging from 0.5Hz to 1.25 Hz, (0.25Hz increments) with amplitude of 45N. The first 6s showed the system responding to a 0.5Hz wave, following 4 s at 0.75Hz. The next 2s show 1Hz and lastly 1.25Hz. The range was selected to include conservatively the fastest dynamic expected to occur during actual palpations. Figure 10 showed some lag during deflation but fast and accurate response for inflation at all frequencies. As the frequency increases, the error during deflation was more apparent.

The forces recorded during four actual palpations were first applied on the sigmoid/hepatic region, similar to Figure 1a, with some minor repositioning during the interaction over a course of 25s. Results of one experiment can be seen in Figure 11. There were distinct periods of the interaction where the control was significantly lagging. This was most prominent in the large deviation which occurred in the example shown at approximately the 15s mark persisting for 3 seconds, at

the 22s mark persisting till the end of the interaction, and to a lesser extent during the short exchange at the 20s mark. At the 8s mark the force dropped dramatically over approximately 45N, during minor repositioning. In this case, the dynamic performance of the fuzzy control was satisfactory, showing small delay between reference and measured force with a tracing error of less than 230ms. In general, over the course of the interaction, the dynamic response of the bladder was very favourable, showing very low tracing error.

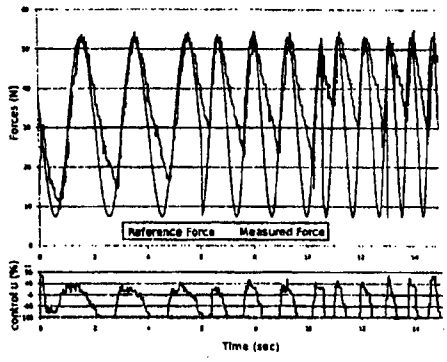

Figure 10: Sinusoidal inputs from 0.5Hz to 1 .25Hz with 0.25 increments over 15 seconds with control output u below.

7. Discussion

In Figure 9 the settling time for the step response differed between the positive and negative step size. This was attributed to the large difference in flow rates between valve A and B. The negative step response highlighted this difference with a 20.9% increase in settling time for 39N to 85N step inputs. During this step size the bladder was inflated to the maximum volume and was constrained by the outer mesh. In the lower step from 0N-39N this was not the case as the negative step response exhibited the characteristic of exponential decay. This

resulted in negative step response settling time 89.5% larger than the positive step response settling time, highlighting the large difference in deflation and inflation rates, especially at low forces.

The sinusoidal results highlighted this limitation even at low frequencies. This is the result of using an exhaust connected to atmospheric pressure while the input was connected to 100 kPa. This limitation could be alleviated and the bandwidth expanded by using a negative exhaust pressure. Similarly Figure 11 showed two large deviations from the reference force set-points at the 15s and 22s marks. At these times the user had disengaged the haptic device to either reposition their hands or to terminate the interaction. The contact with the bladder was lost and the need for responsiveness or high dynamic performance not needed, as the user would not be aware of the slow deflation response. Dangerous manoeuvres involving fast disengaging and reengaging are rarely employed and we did not consider these in our abdominal force simulation scenarios.

As expected, at the 8s mark, a similar deflation occurred across 45N but did not show this limitation. At that time, the user repositioned his/her hands whilst remaining in contact with the abdomen, a more realistic clinical case. The response of the fuzzy controller was able to trace the drop in force with a maximum delay of230rns, which would have negligible significance to the user. Overall, disregarding points where the user lost contact with the device, the haptic device traced the reference force within an average 300ms delay, 94.2% of the time. The

results depicted a good dynamic performance for simulating forces whilst the user was engaged in an active palpation.

The fuzzy controller we presented was compensating very well for most non-linearities in the system and provided accurate and fast force control for frequencies below 0.5Hz and for positive reference forces of at least 1.25Hz. Higher frequencies and fidelity during retraction could be attained by increasing the deflation rate through an alternative system design.

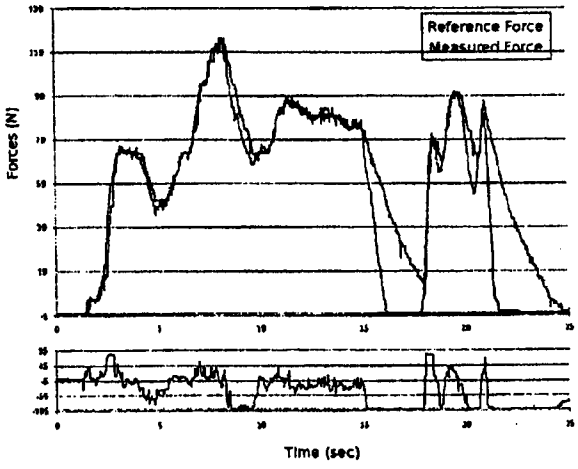

Figure 11: Using force data gathered from palpations over a 25 second interaction with control output u below.

As a whole, the haptic device was able to control the resistive forces generated by the air bladder to simulate forces likely to be experienced during abdominal palpation. The deflation flow rate was an anticipated non-linearity which affected the dynamic response for high frequency inputs. The fuzzy control performed admirably showing very low steady-state error and high dynamic performance. In situations which did not involve rapid deflation it was able to track, simulate and trace the reference input force.

8. Conclusion

In this paper, we have described a new implementation of pneumatic piston position control and air muscle technology to develop a haptic interface capable of simulating forces experienced during abdominal palpation. The use of an innovative pressure variant approach to PWM valve control mitigated the common issue of deadband and modeled the zero flow rate over the operating pressure range (0-8kPa). This was an important factor in reducing steady-state error, overshoot and oscillation.

Experiments were conducted on the haptic device showing excellent accuracy, steady-state and dynamic performance of the fuzzy controller. An issue was identified with the deflation flow rate on the exhaust valve during low bladder pressure, during the unimportant phases of the palpation procedure where the hands are removed from the abdomen.

Both the steady-state and dynamic response of the haptic device were sufficient to follow recorded forces during actual palpation with a delay of less than 230ms repositioning, a value that we expect to be unnoticeable during hands repositioning during the simulation.

9. Acknowledgements

We would like to acknowledge Queensland Centre for Advanced Technologies (QCAT) in Brisbane Australia, especially Jonathan Roberts, who provided advice and

necessary equipment and workspace to develop and test the haptic device.

10. References

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CLAIMS

1. A simulator apparatus for simulating a response to a tactile medical examination of a patient, comprising a first tactile feedback arrangement and a second tactile feedback arrangement, the first and second tactile feedback arrangement being arranged together to provide a response simulating patient surface tactile feedback and a patient body type.

2. An apparatus in accordance with claim 1, wherein the first tactile feedback arrangement is a first fluid operated bladder.

3. An apparatus in accordance with claim 2, wherein the second tactile feedback arrangement comprises a platform body arranged, in operation to support the first fluid operated bladder.

4. An apparatus in accordance with claim 3, wherein the platform body is arranged to vary in height relative to the first fluid operated bladder.

5. An apparatus in accordance with claim 3 or claim 4 wherein the platform body is a second fluid operated bladder.

6. An apparatus in accordance with any one of claims 2 to 5, wherein the first fluid operated bladder and platform body are volume constrained by an enclosure.

7. An apparatus in accordance with claim 6, wherein the enclosure is a webbing placed about the first fluid operated bladder and platform body.

8. An apparatus in accordance with any one of the preceding claims, further comprising a probe body, arranged to represent a moveable probe within a patient.

9. An apparatus in accordance with claim 8, wherein the probe body is positioned between the first and second tactile feedback arrangements.

10. A simulator apparatus for simulating a response to a tactile medical examination of a patient, comprising a first tactile feedback arrangement and a second tactile feedback arrangement, the first tactile feedback arrangement comprising a body arranged to provide a tactile response to manipulation of the body by an operative, and a second tactile feedback arrangement comprising a further body forming an interface with the first tactile feedback arrangement, and being operable to raise or lower the interface to bring the interface into or out of haptic range of the first tactile feedback arrangement.

11. A simulator apparatus for simulating a response to a tactile medical examination of a patient, comprising a first fluid operated bladder and a second fluid operated bladder, wherein the first fluid operated bladder is positioned, in operation, on top of the second fluid operated bladder.

12. A simulator system, comprising a plurality of simulator apparatus in accordance with any one of claims 1 to 9 or 10 or 11, positioned with respect to each other to represent a part of a patient's body, for simulating a response to a tactile medical examination of the part of the patient's body.

13. A mannequin, representing a patient body, and mounting a system in accordance with claim 12.

14. A method of simulating a response to a tactile medical examination of a patient, comprising the steps of providing a tactile feedback response, simulating patient surface tactile feedback and a patient body type.

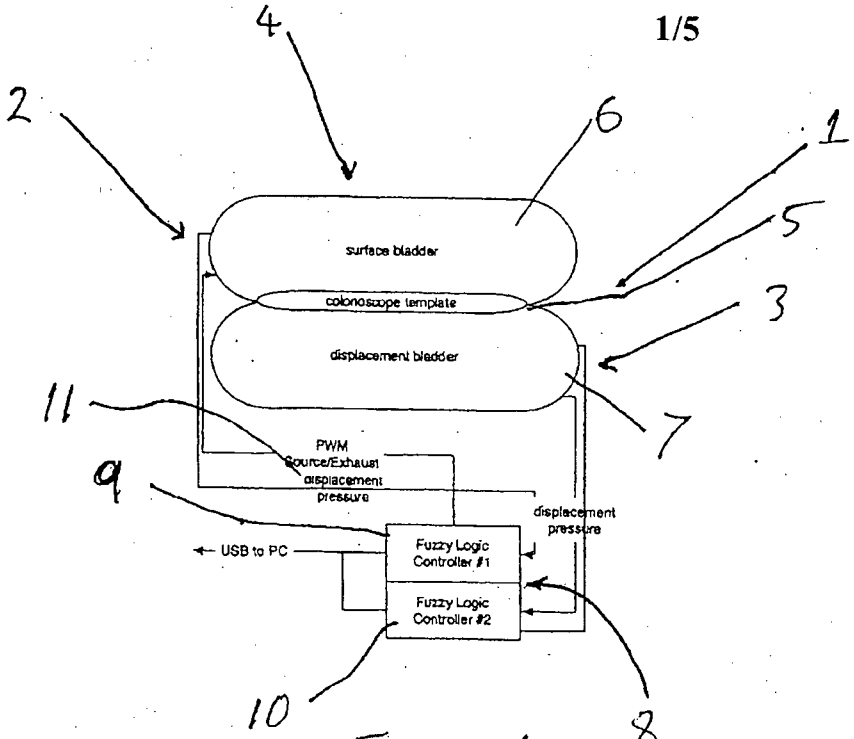

FIGURE 1

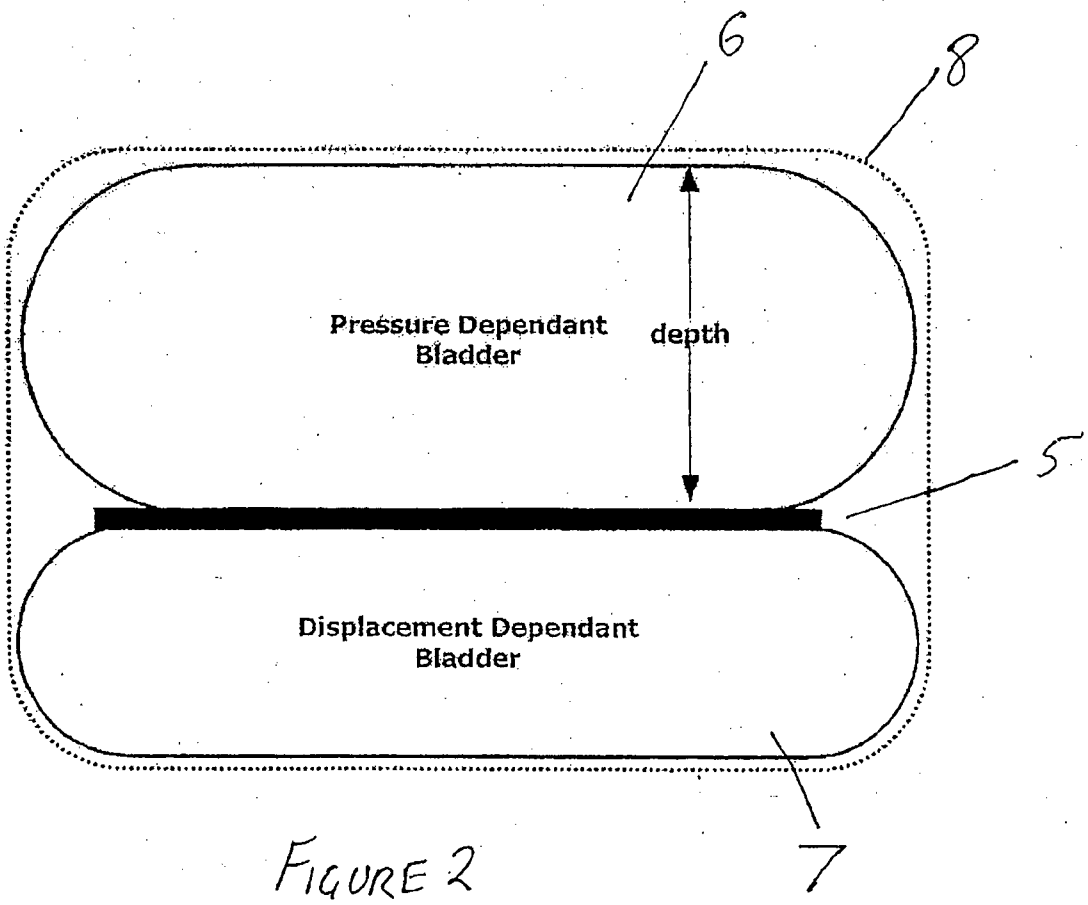

FIGURE 2

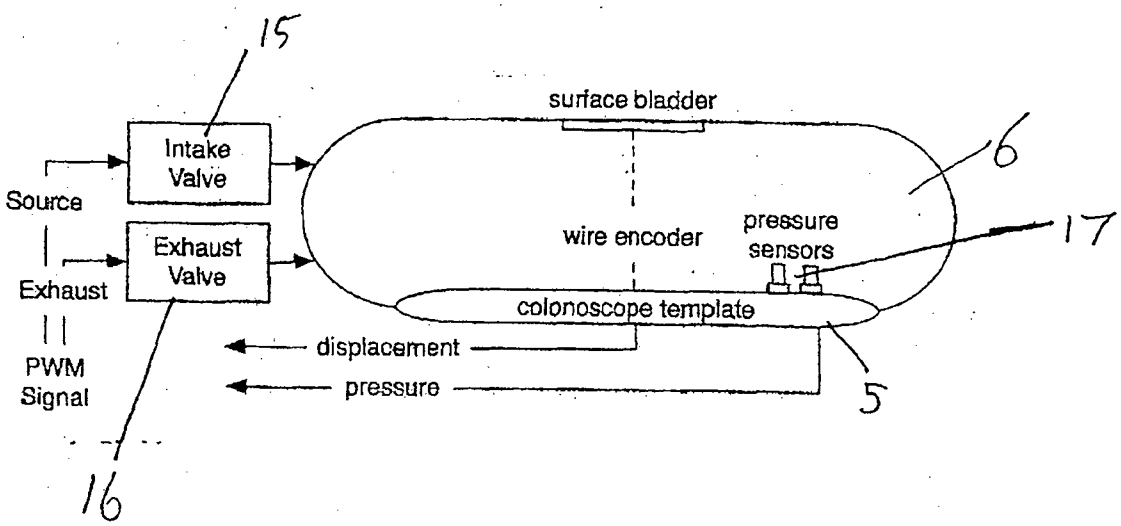

FIGURE 3

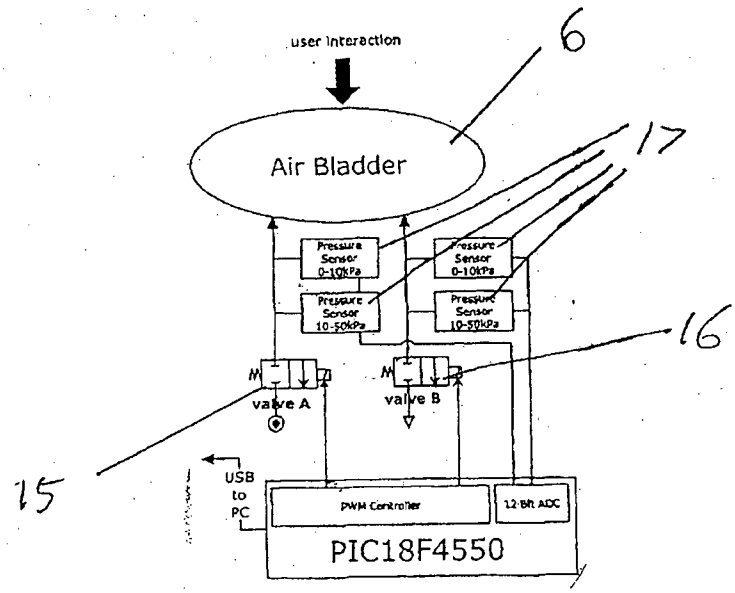

FIGURE 4

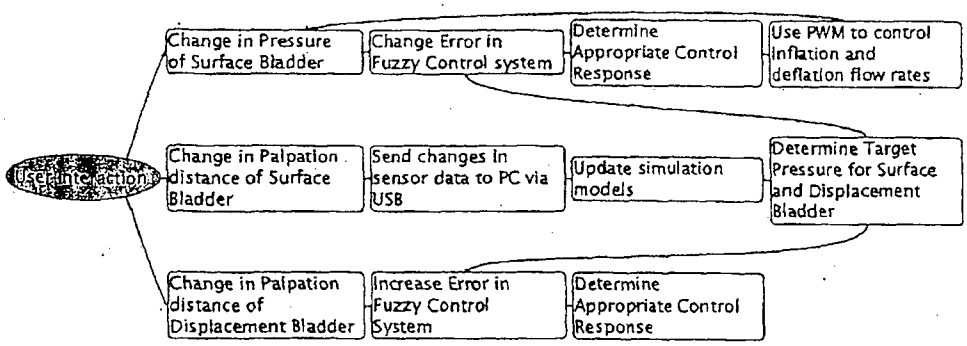

FIGURE 5

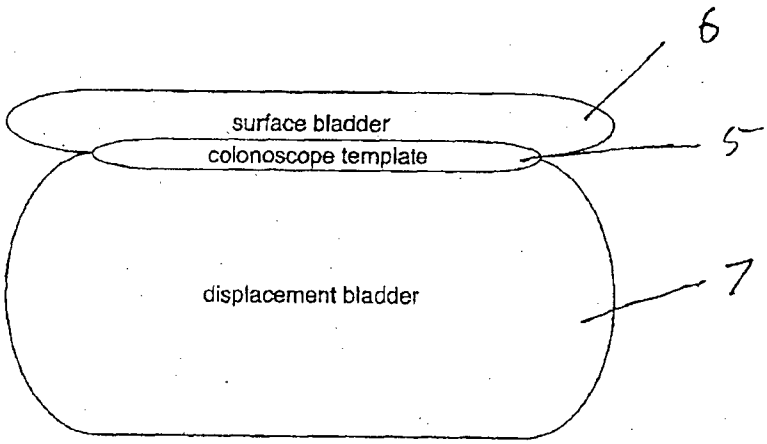

FIGURE 6

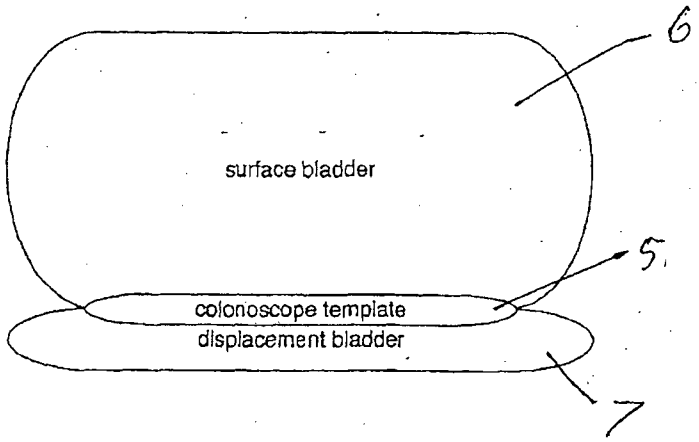

FIGURE 7

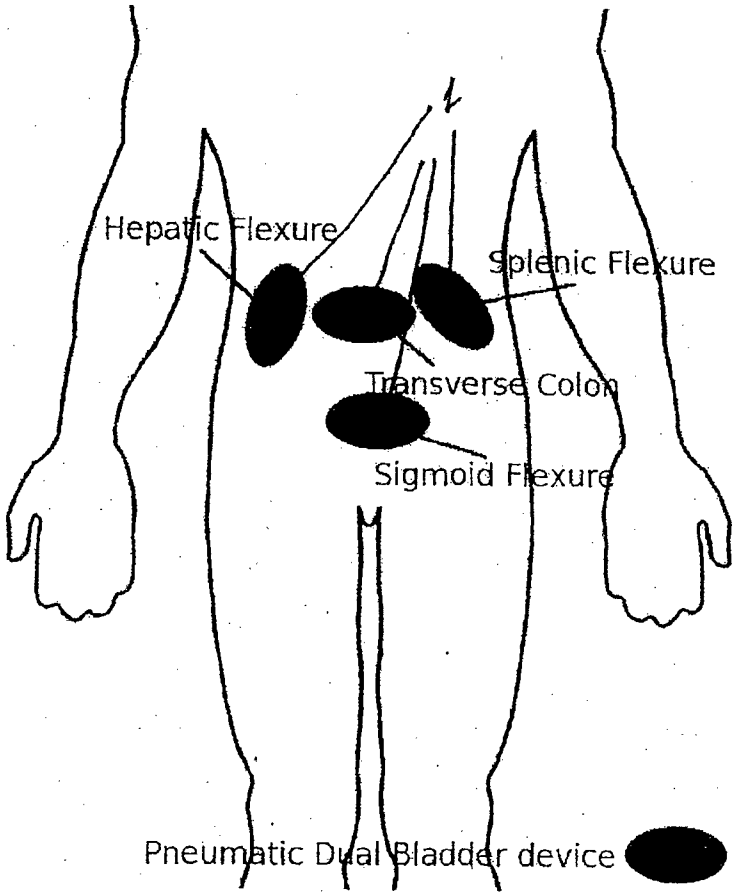
Hepatic Flexure
Splenic Flexure
Transverse Colon
Sigmoid Flexure
Pneumatic Dual Bladder device

FIGURE 8

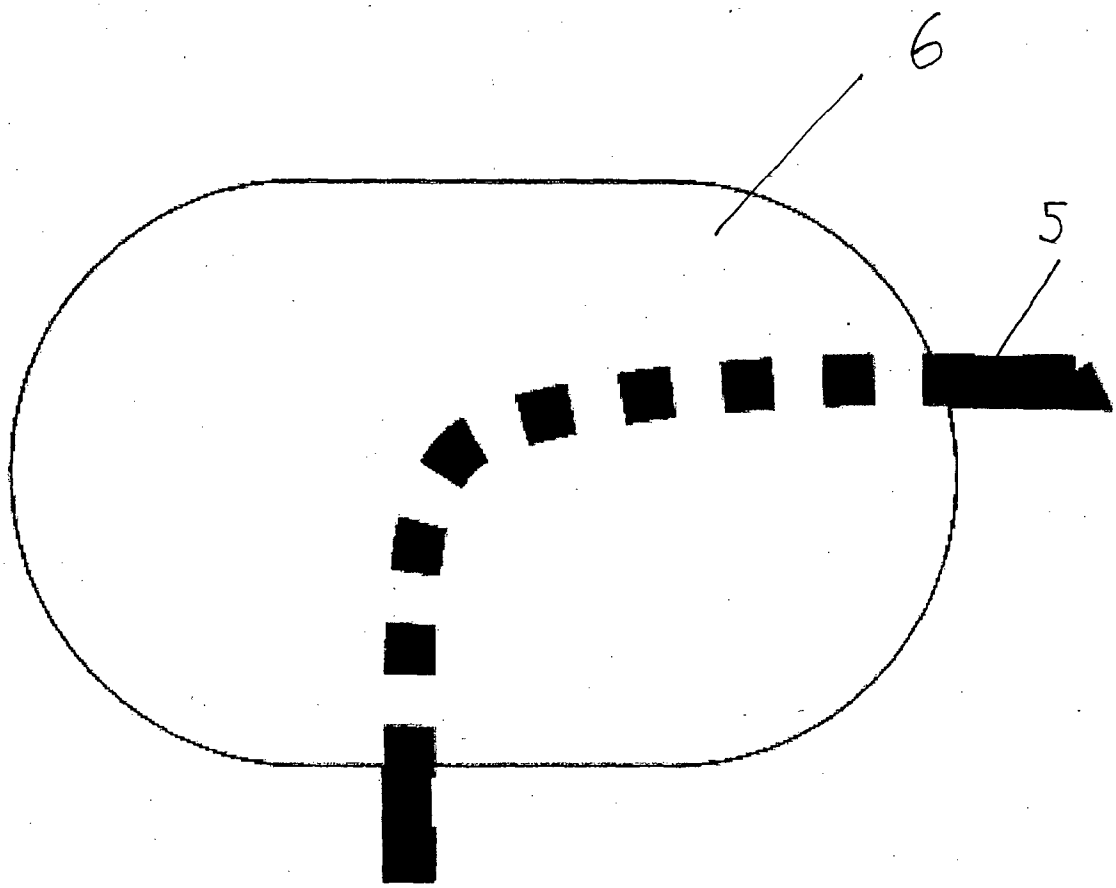

FIGURE 9

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU2011/000370

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl.

G09B 23/28 (2006.01) ***G09B 9/00*** (2006.01)

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
WPI, EPODOC: IPC and EC G09B 9/-, 23/- and A61B/- & Keywords: model, mannequin, dummy, train, simulate, haptic, tactile, palpate, examine, feedback, response, bladder, inflate, scope, probe; and like terms.
Google Patent Keywords: model, mannequin, haptic, tactile, air, bladder, feedback and like terms

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
X Y	US 2007/0003917 A1 (KITCHING et al.) 4 January 2007 Figures 1-4; paragraphs [0036]-[0039], [0043]-[0045], [0061]-[0064], [0069], [0071]-[0074]	1-7, 10-14 8, 9
X	US 6945783 B2 (WEISSMAN et al.) 20 September 2005 Figure 2; column 2, lines 5-25 and 62-65; column 3, lines 5-24 and 29-48; column 4, lines 2-5 and 59-67; column 5, lines 1-8	1-3, 6, 10-12, 14
X	US 5249968 A (BRAULT et al.) 5 October 1993 Figure 2; column 1, lines 5-10; column 3, lines 52-60; column 4, lines 3-6; column 5, lines 7-13; column 6, lines 8-11	1, 2, 6, 14
Y	US 6939138 B2 (CHOSACK et al.) 6 September 2005 Abstract; column 3, lines 50-64	8, 9

☐ Further documents are listed in the continuation of Box C ☒ See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)

"O" document referring to an oral disclosure, use, exhibition or other means

"P" document published prior to the international filing date but later than the priority date claimed

"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention

"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art

"&" document member of the same patent family

Date of the actual completion of the international search	Date of mailing of the international search report
09 May 2011	**17 MAY 2011**
Name and mailing address of the ISA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. +61 2 6283 7999	Authorized officer **WAN KIT CHAN** AUSTRALIAN PATENT OFFICE (ISO 9001 Quality Certified Service) Telephone No : +61 2 6283 2974

INTERNATIONAL SEARCH REPORT

Information on patent family members

International application No.

PCT/AU2011/000370

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	2007003917	EP	1616315	WO	2004095398		
US	6945783	US	2003219705				
US	5249968	AU	14522/92	CA	2040710	WO	9218966
US	6939138	AU	50601/01	EP	1275098	US	2003091967
		WO	0178039				

Due to data integration issues this family listing may not include 10 digit Australian applications filed since May 2001.

END OF ANNEX