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Design and Development of Soft Robot for Head and Neck Cancer Radiotherapy

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ABSTRACT

In this paper, we present a new design of head immobilization system for head and neck (H&N) cancer radiotherapy. The immobilization system consists of a radio-translucent 3D printed thermoplastic, helmet-like structure open partially in the front and custom-made fluidic actuators. The system can be actuated using compressed air to induce pitch and roll rotations. The mechatronic components of the system include two valves for each chamber, a microcontroller, airflow sensor, power supply, a compressed air source, and one pump to remove air. All of these are kept away from the patient's head so as not to interfere with the radiation beams, and radiation transparent tubing are connected with the chambers to the mechatronic components. The design provides comfort to patients due to curvature fit of patient head/neck and the use of soft actuators. The material used for custom-made actuators is silicone elastomer Eco-Flex 30. The main design variables are air chamber size, air pressure, volume flow rate, number of chambers, layers of sealing and shore hardness of the elastomer. Various arrangements of actuators and designs are investigated. The fabricated new actuators specifically designed for the positioning system were characterized using a humanoid robot head that mimics an actual patient's head. We hope that the new device will give comfort to patients due to curvature fit of patients' head/neck and the soft compliant actuators.

Key words: Soft actuators, head positioning system, humanoid head, silicone elastomer

1. INTRODUCTION

Radiation therapy is one of the definitive treatment regimens for the head-and-neck (H&N) cancer. Accurate patient positioning is critical and challenging for head-and-neck (H&N) cancer radiotherapy [1, 2] due to the proximity of critical organs, such as the optic nerves, spinal cord, and salivary glands, to treatment target. The impact of positioning accuracy is amplified with intensity modulated radiotherapy (IMRT), where highly conformal doses are delivered to target(s) while a rapid dose fall-off is designed to spare critical organs . Studies have demonstrated both improved survival [3] and quality of life [4] with IMRT. However, the use of such a conformal radiation dose is accompanied by a high risk of loco-regional failure and toxicity due to dose deviation that is unaccounted for [1, 2]. Several clinical studies have reported a strong correlation between loco-regional failures/toxicity and dose deviation [5]·[6],[7], which are primarily a result of positioning errors. Based on these observations, we postulate that accurate patient positioning will significantly improve treatment quality by reducing target dose deviation with accurate beam delivery and increasing critical organ dose sparing with margin reduction. The accuracy of current couch and mask based immobilization system is < 1mm. However, they do not offer comfort to the patient due to the face mask that is being used for hours during the treatment.

Current H&N patient positioning systems oversimplify patients' motion in both the space and time domains and do not account for inter- and intra-fractional anatomic variation throughout treatment. For example, the cervical spine is prone to

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deformation, and its posture varies from day to day. However, non-rigid position adjustment is rarely imposed with current systems, even though such variation is measurable with daily on-board Cone-beam CT (CBCT). During treatment, a full-head thermoplastic mask is used to immobilize the patient and is intended to cast the patient as a static model. However, such a simplified static model does not reflect reality, since voluntary and involuntary patient motion cannot be avoided. Moreover, the head mask is not only uncomfortable for many patients, but also intolerable for some, who suffer from claustrophobia**.** There are different types of H&N positioning options and treatments. **Fig. 1** shows a thermoplastic mask on a patient's head and a radiation beam applied to area of interest.

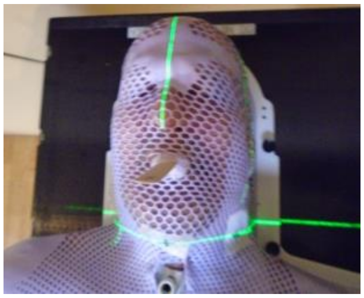


Fig.1 Thermoplastic mask used in Head and Neck cancer radiotherapy.

In this paper, we show a new design consisting of a radio-translucent 3D printed material, helmet-like structure open in the front and partially on the top. Custom-made air chamber, set below and around patient's head, can be actuated cooperatively to induce pitch and roll rotations and anterior-posterior (AP) translation. The mechatronic components of the system include two valves for each chamber, a microcontroller, airflow sensor, power supply, a compressed air source, and one pump to remove air. All of these are be kept away from the patient's head so as not to interfere with the radiation beams, and radiation transparent tubing will connect the chambers to the mechatronic components. Multiple layers of sealing are needed to the air chambers to prevent air leaking. The design provides comfort to patients due to curvature fit of patient head/neck and the softness of the soft actuator. Different silicone elastomer can be used for making the custom-made actuators. We used Eco-Flex 30 silicone to make air chambers by casting in a mold. We tested the Eco-flex 30 and found out that it can be stretched up to 600% strain at 0.6Mpa. Other types of Eco-Flex 50 has been used for similar purpose, which has shore hardness of 50, elasticity up to 200% strain and 0.25 MPa stress and can sustain up to 1 million cycles[8]. The overall cost of the positioning systems is low, since silicone elastomer are inexpensive ($180 per gallon). The main design variables are air chamber size (V), air pressure (P), volume flow rate (Q), number of chambers (n), thickness of silicone layers (L) and cost (C). The head positioning system needs design and development of new actuators specifically designed for the positioning system. This will help the closed loop control of the actuators to achieve high accuracy and not limited by hardware capabilities. All the performance indices of the actuator will be determined based on the matrix presented in the literature[9] [10]. It is important to note that involuntary patient's movement during radiotherapy will be interrupted and corrected by the closed loop control system. Therefore, our current design does not require an immobilization mask.

2. MECHANICAL DESIGN AND PROTOTYPE OF THE POSITIONING SYSTEM

The goal here is to construct a radio-translucent and open-face soft robot for personalized patient H&N position system. Over a year, we have designed three designs of the soft robot as illustrated computer-aid design (CAD) in **Fig.2**. Design 1 has three inflatable pillows and it was integrated with a multi-level vision based control system for motion control evaluation. Design 2 has eight smaller pillows as shown in the figure (b). Design 3 is a new design, which is being investigated and the focus of this paper. Essentially, design 3 uses very small inflatable silicone structure that inflated and deflates as shown in (d) and (e) when a pressure is supplied.

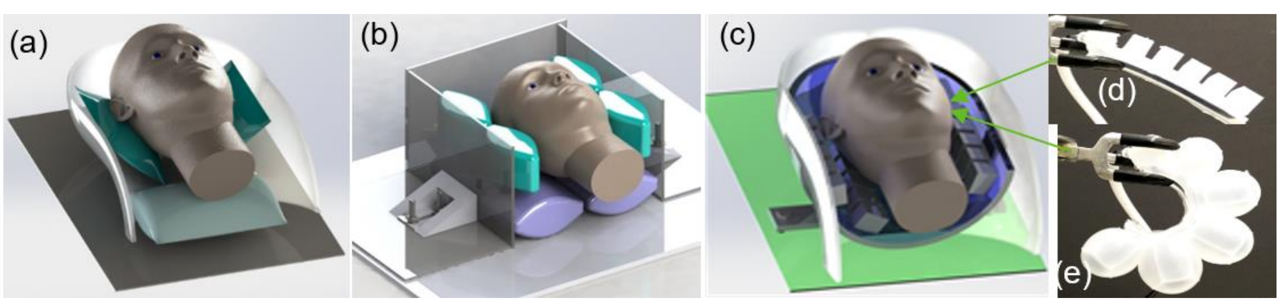


Fig. 2. Soft robot design path (a) Design 1: large commercial air pillow has already been integrated with a visual feed-back control system. (b) Design 2: adjustable frame and small air pillows that are mechanically validated. (c) Design 3 is a new PnueNet based positioning system and a 3D-printer.

Fig. 3(a) is a picture of head positioning system in design 2. The frame was built using a laser cut Plexiglas, which is movable to accommodate different sizes of patients' head. The inflatable bladders, fixed in the frame beneath head, were pumped manually like we do in blood pressure measurement (inset of **Fig. 3(a)).** An adult size head model was 3D printed and weighted accurately. The head has a ball – socket joint at the neck. Tests were made to ensure the capability of small angular movements by controlling each bladder separately and in combination. Features of the design include comfort, fine resolution, low cost and safety. Actuation of the head was performed, and **Fig. 3 (b) - (c)** show pitching and rolling motion of +/- 5° from normal position respectively. The angular position versus time was verified by a Phantom high-speed camera (VRI-MICROEX2, Vision Research Inc. NJ, USA). Also, IMU was mounted on the head to track angle data. The reachable positions of the head can be +/- 45° but we limited our test to be in the range +/-5°, which covers adjustment range common to clinical practice. The resolution of the head movement was ~ +/-0.5° using hand pumping. We can further make fine angular movement (resolution) <0.5° by changing the bladder size and the air pressure. Design 2 was also tested in similar manner as design 1.

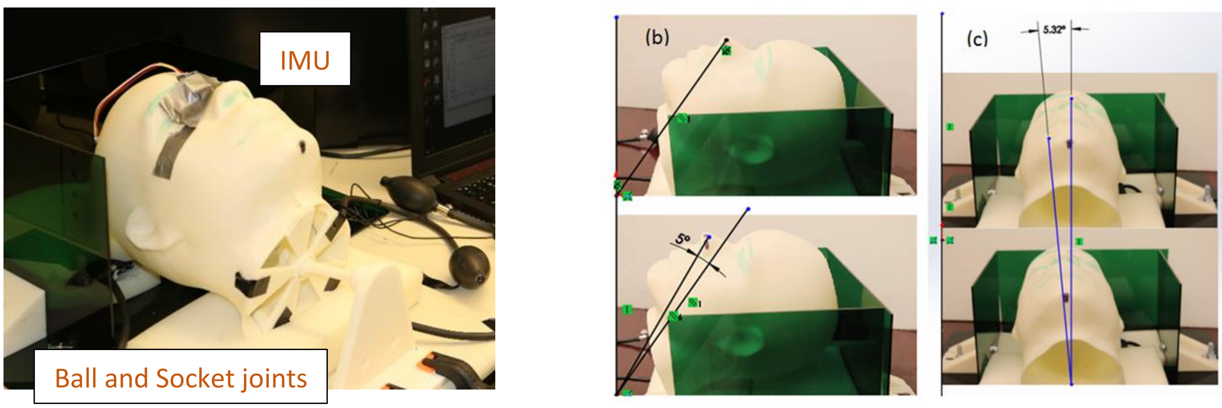


Fig. 3 Design 1 soft robot postioning system: (a) adjustable frame with two air bladders beneath a dymmy head. The dummy head can be accurately rotated in two dimension (b) pitch and (c) yawing within +/-5°.

2.1 Actuators design and fabrication

For the positioning system design, three custom-made actuators were necessary. We created the actuators by making a mold using a 3D printer, the model was based on the dimensions provided by soft robotic tool kit, and casting a mixture of silicone Eco Flex 30 Part A and Part B in a ratio of 1:1. After this, the mixture was placed in a vacuum chamber to remove all the air bubbles trapped inside the silicone due to hand mixing of part A and part B to initiate the cross linking of the polymers. **Fig.4 (i)** shows the silicone during the vacuum process. After the vacuum process is complete, the mold was set in a fixed position and then the silicone was poured into the mold. After that, the mold was put in an ultrasonic mixer for 25 minutes. The mixer consists of a small piezo electric vibrating motor. The device is an enclosed water bath, when the piezoelectric motor vibrates the vibrations are translated into the water which is surrounding the whole mold. The fast vibrations agitate the particles of the silicone which increases the speed of the cross-linking process. Here, the ultrasonic mixer is able to reduce the curing time by 162% (25 minutes vs 240 minutes). This part of the silicone was the upper portion of the actuator and can be seen in **Fig.4c.** After this we took another mold for creating the base of the actuator. The eco-flex 35 fast silicone was used. A pneumatic tube which was pierced at equal locations for the inflation of the actuator was placed inside the actuator. After this the silicone was poured into the mold as shown in **Fig.4e** and was cured till about 75% and the upper part of the actuator was placed over it completing the final product. After curing the actuator was used for the experiment.

2.2 Design considerations and variables of the actuators

We examined all variables of the head positioning system using Pugh matrix (Decision-matrix) to determine the best performance. Various arrangements of actuators and design is being implemented. The fabricated new actuators specifically designed for the positioning system are characterized to see any practical issues. This will help the closed loop control of the actuators to achieve high accuracy and not limited by hardware capabilities. Important parameters are strain vs. stress, input pressure vs. strain, noise levels vs. input pressure, frequency response, and life cycle and reliability.

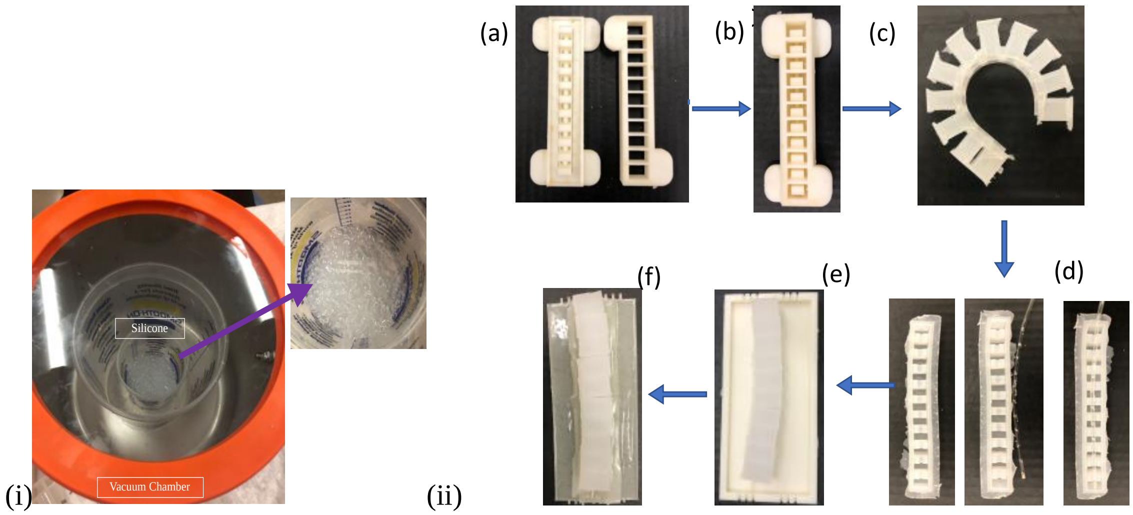


Fig.4: (i) Silicone during vacuum chamber. Zoomed in picture shows bubbling due to the release of trapped air. (ii) Manufacturing of soft pneumatic actuator. (a-b) Assembly of 3D printed mold, (c). Soft actuator after molding, (d) Addition of tube for airflow control, (e) Addition of bottom silicone part of actuator (f) Final actuator ready for use.

2.2.1 Experimental study for constant pressure vs time

We tested the inflation of the soft pneumatic actuators using the experimental setup. The experimental setup includes the actuator, the actuating circuit consisting of Arduino board and solenoid valves, compressor and pneumatic pipes. The actuator was to inflate for a specific period at constant pressure of 7psi. The code was modified in such a way that the time for inflation was controlled by controlling the solenoid valves. The inflation was ON for 250 milliseconds for the first cycle and then repeated for multiple cycles with a step size of 250 milliseconds till the value of 2500 milliseconds was reached where the actuator overextended and was no longer operational. This experiment was done to check the amount of displacement an actuator can provide to the human head during the therapy at constant pressure conditions. **Fig.5** shows the actuator displacement vs time.

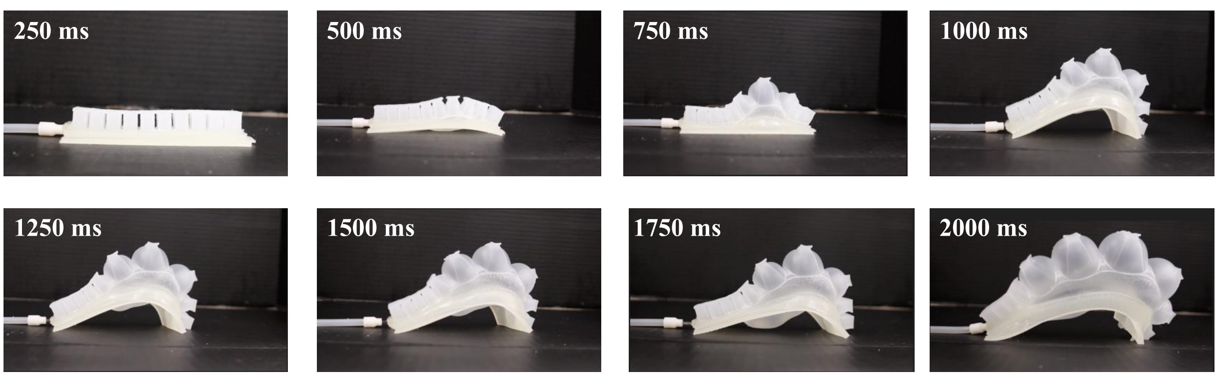


Fig.5: Snapshot of soft actuator maximum deformation at 250 ms time intervals for a 7psi input pressure

Fig.6 shows the displacement of the soft actuator without the inserted tube at 2250ms actuation. It is to be noted that even though it fully actuated it eventually over extended and was no longer operational. It is recommended to increase the thickness of the silicone for longer time intervals**.** It was observed that the actuator was inflated from the middle portion in the beginning and then gradually from the side portions as seen in fig (5). The main reason is the design of the actuators, as the ends are designed to be thicker than the middle. Therefore, the thinner sections will inflate first due to the lowest resistivity. Moreover, as we increase the amount of time the solenoid valve enabled more flow and more displacement was seen in the actuator.

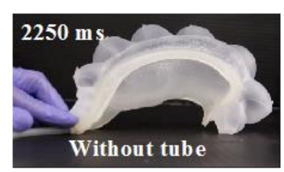


Fig.6: Soft actuator without inserted tube actuated for 2250 ms at 7psi pressure

3. EXPERIMENTAL SETUP

We did preliminary test on the newly fabricated actuators as well as on the head mounted on the actuator array (**Fig.7**). The experimental setup includes a compressor, Arduino controller, solenoid valve, a video camera and a PC.

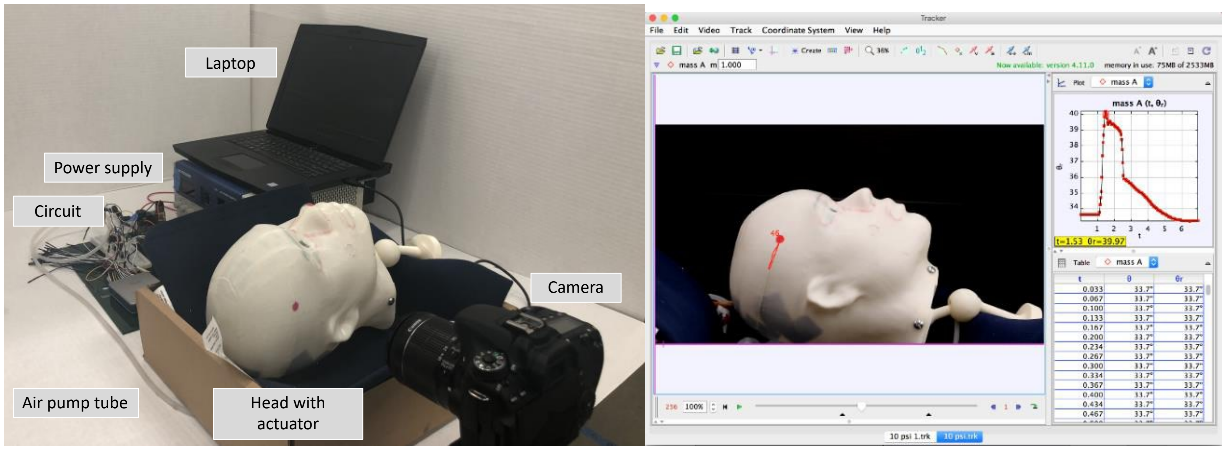


Fig.7 (a) Experimental set up for data tracking which includes laptop, an actuation circuit, a camera, and an air pump. (b) Snap shot of tracker program used to gather data for analysis.

The pressure in the compressor was set to some amplitude and the time was controlled by a delay loop in the Arduino program. The video was processed using a tracking software (Tracker). **Fig.8(a)** displays the actuating circuit used for the experiment. The actuating circuit consist of Arduino Uno board connected to the solenoid valves via resistors and pressure sensors. The solenoid values get their input from a compressor (California Air tools). The solenoid valves are connected to power supply at 12 V. This arrangement is done to energize the circuit. The energizing and de-energizing actions of the circuit are controlled by the Arduino code. In **Fig.8**, we have also mentioned a circuit consisting of NI-DAQ. This circuit can be used for measuring the actual air pressure in the actuator with the help of pressure sensor and NI-LabView. The connections of the DAQ are displayed in **Fig.10(b)**.

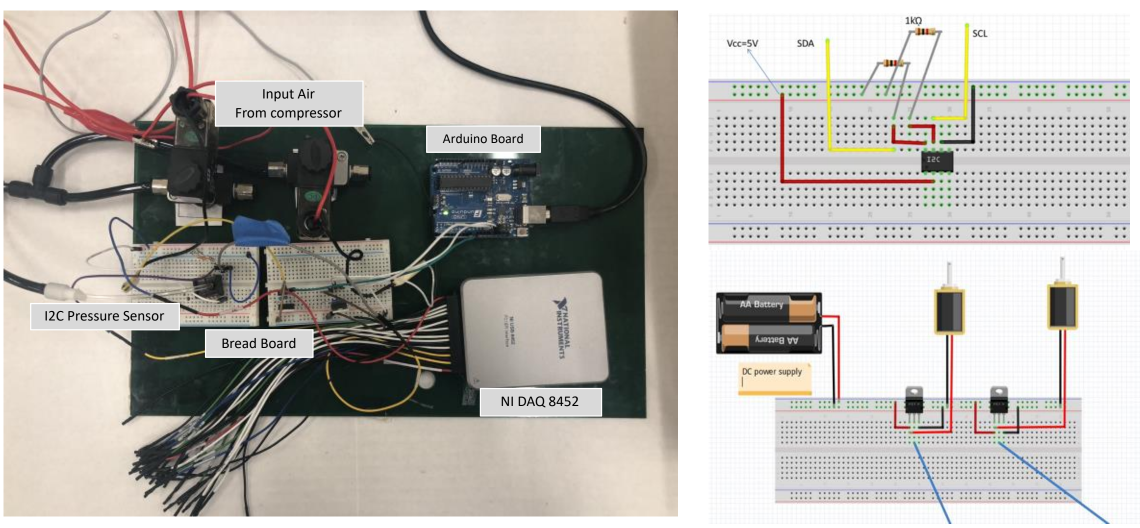


Fig.8: (a) Actuation circuit. (b): Schematic diagram of the actuation circuit and I2C connections on the left and NI-DAQ connections on right

4. RESULTS AND DISCUSSION

The head positioning experiment was done to produce several head movements such as rolling, pitching, and yawing. The combination of these movements will also allow for more degrees of freedom for head positioning control. The head position was tested at different pressures (7-14psi). One of the major issues observed is that the silicone samples are completely flexible which causes them to curve while actuating especially at high pressures such as 14 psi. Some solutions to that is the addition to spring or thin wood panels. The addition of spring steel is not practical for this application as it is a metallic material, which is not safe for this therapy application. The addition of the wood panel or flexible thermoplastic will cause the silicone to rip due to the geometry of the silicone while inflating. Although there are several safety issues, the soft silicone skin allows for maximum comfort for the patient. The pillow like structure is soft which gives the patient the feeling of laying their head on a pillow. The elimination of the mask typically used in this therapy will also reduce the stress and anxiety of the patient. The soft actuator can be easily controlled and manufactured into many shapes and sizes that can accommodate the patient. **Fig. 9** shows several snapshots of head moving using the soft silicone actuator. The experiment was conducted at 7, 10 and 14 psi. It is observed that for the 3mm thick silicone, higher pressure will cause the chambers to burst. Angular displacement was conducted on several head movements such as pitching and yawing. A red point was added to the tip of the nose, the program (tracker) was used to calculate the displacement, and the results are plotted in MATLAB. **Fig. 10 (a)** shows the angle displacement obtained from pitching head movement. At 14 psi, the head lifts up at a maximum angle of 7^{o}, while at 10psi and 7 psi it produces 4^{o} and 3^{o}. The desired patient head motion in H&N cancer therapy is about 5^{o}. Therefore, low pressure is sufficient to lift a head up. **Fig.10(b)** shows that at the higher pressure 14psi produces a yawing movement up to 60^{o}. While at 10 and 7 psi it produces 20^{o} and 17^{o} respectively

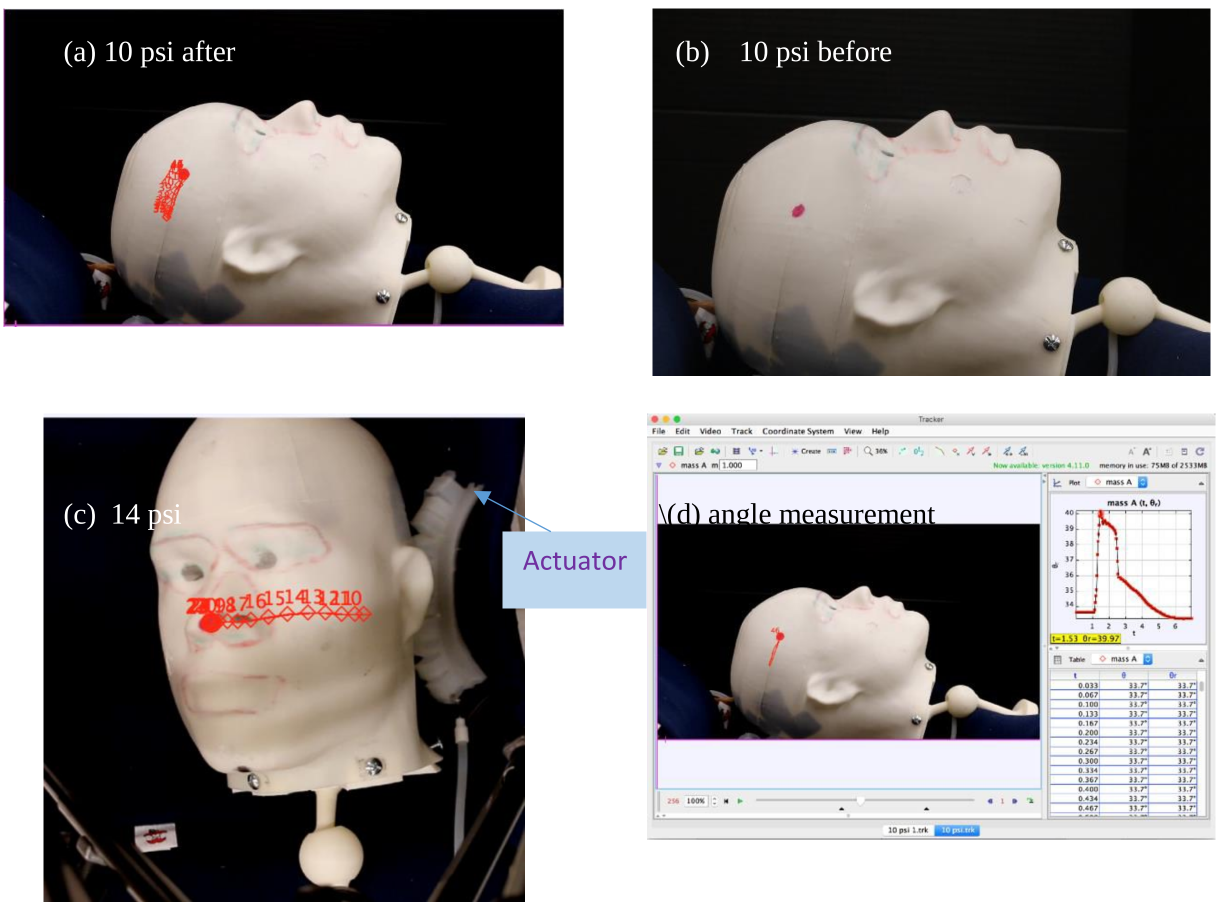
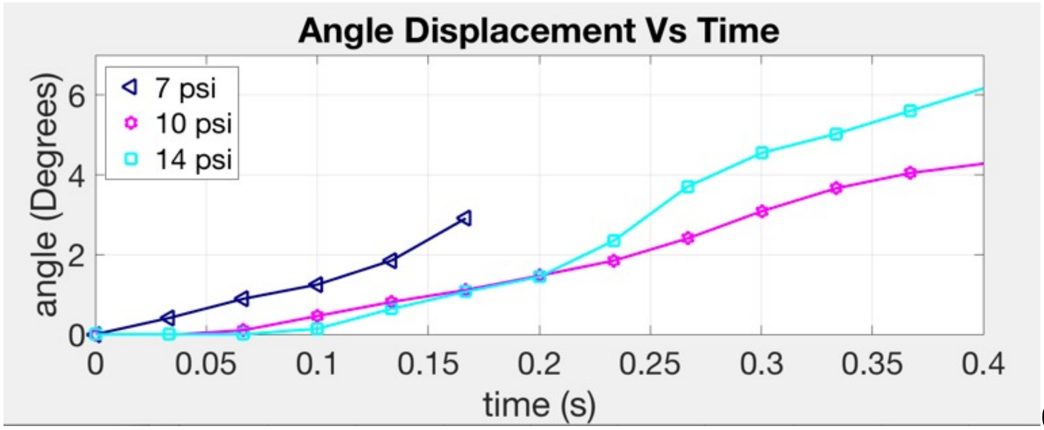
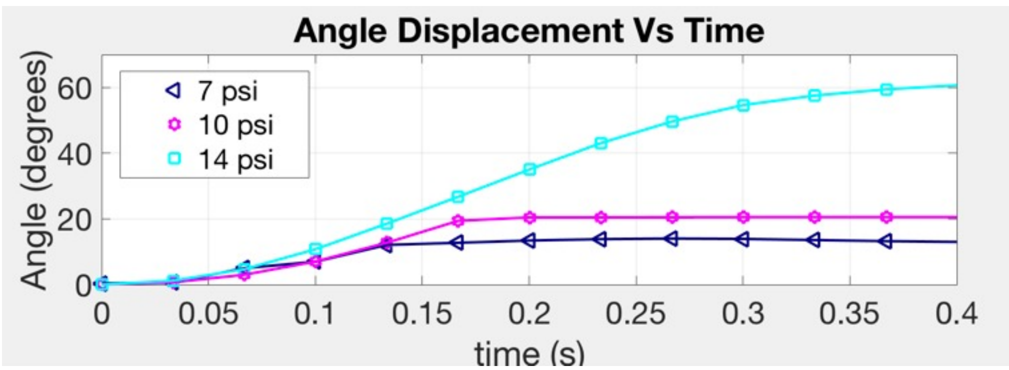


Fig. 9: Snap shot of head when the actuator is inflated at different pressure. (a) pitching movement, (b)Initial pitching position, (c) yawing movement



(a)



(b)

Fig. 10: Angle displacement at 7psi, 10psi, and 14psi for 250ms (a) Pitching head movement, 7psi data recording was stopped at the above value, (b) yawing head movement.

5. ON THE CONTROL OF THE HEAD POSITION

Fig.11 shows the experimental setup used for closed loop control of the head. For this experiment, an accurate head was 3D printed, featuring a double ball joint neck and weighted to approximately 5kg. The head is supported by three air bladders built as shown in design 2 earlier in section 2– one directly beneath the head and one on both the left and right sides of the head. This allows two rotational degrees of freedom and to raise the head. Each bladder has a pair of proportional valves that regulates airflow in and out of the bladder. A regulated compressed air tank provides air into the bladder. An air pump removes air from the bladder. We used an Ensenso N35 stereo camera, which can deliver a dense point cloud (seen in **Fig. 12**(a)), and use vision algorithms to isolate the head and determine its position and orientation. The image processing is handled by a Windows PC, which calculates the head position and runs all vision-based control calculations. Valve command are sent to a National Instrument myRIO embedded microcontroller that handles all analog and digital I/O and regulates the current-controlled valves. We approximated the nonlinear actions of the air bladders via a Recurrent Neural Network (RNN) using a Long ShortTerm Memory (LSTM). The NN can be seen as a model that remembers effective controls for the adaptation mechanism in the presence of uncertainties and external disturbance. With nonlinearities accounted for by the NN, we employed a model-reference adaptive controller (MRAC) to handle the remaining system components that are well approximated by a linear system. The novelty was the use of LSTM, which continues to update during run time, in place of a static NN[11].Typical experimental results are shown in **Fig.12**(b) and (c), when the head was commanded to be raised to 15mm above the starting height. The head is raised to the correct height in about 10 seconds. The current vision has a noise floor of +/- 2mm and +/-1.5º. This is close to the minimum accuracy for radiation therapy.

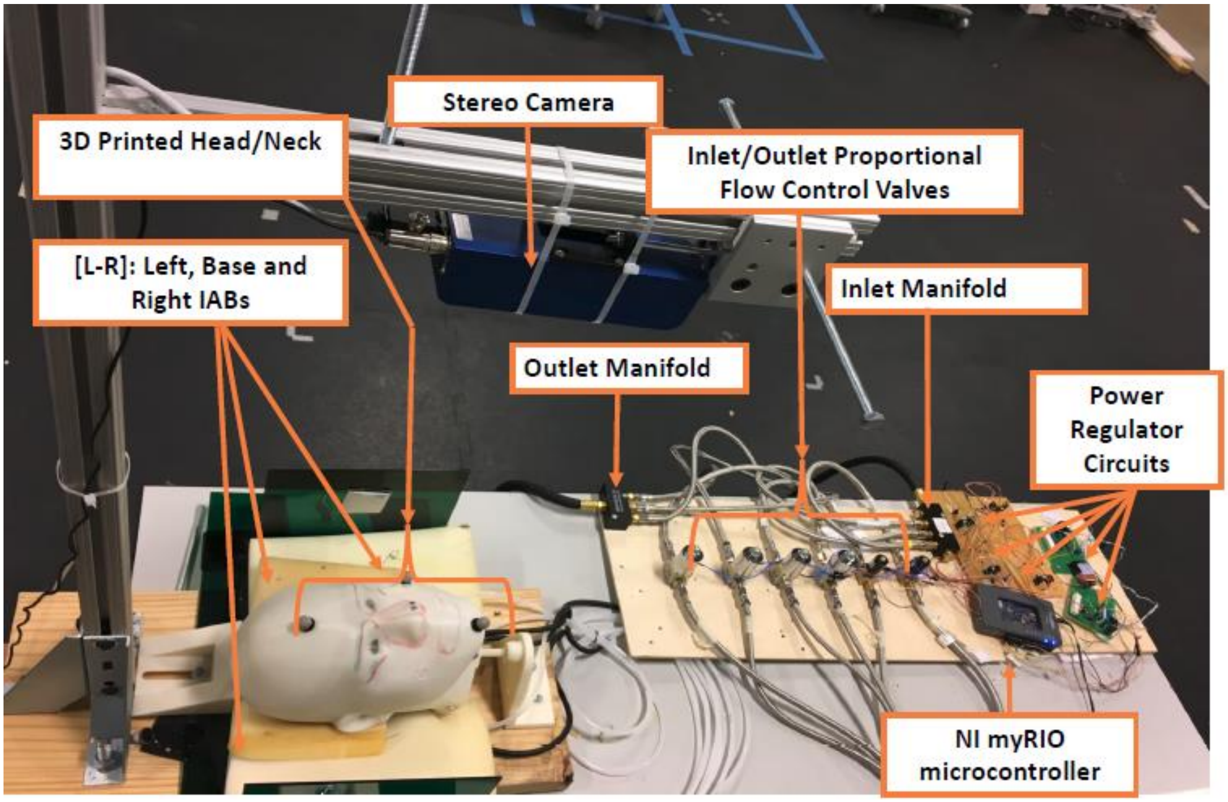


Fig.11 The entire system integrated with control system

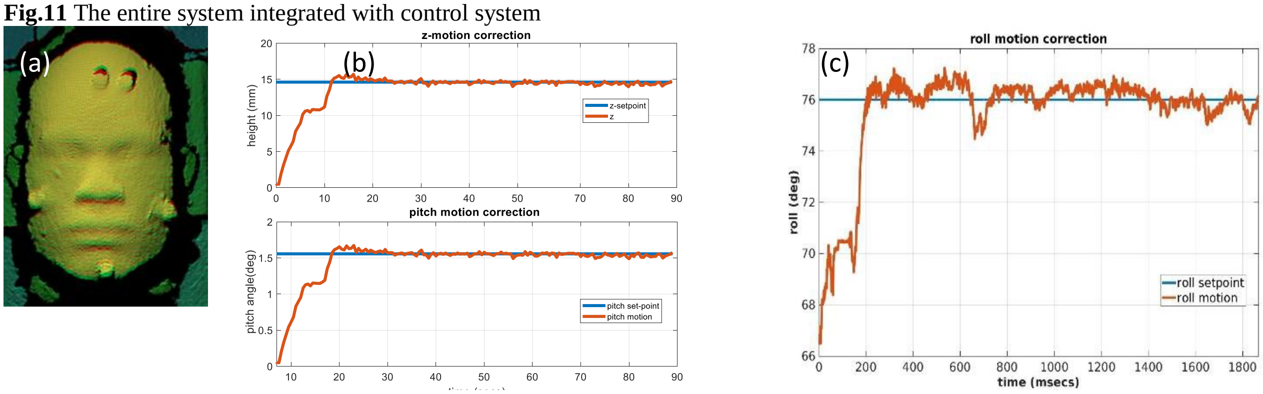


Fig. 12 (a) The face surface extracted from a 3D camera. (b) An example of regulating height and pitch angle determined from surface images. (c) An example of regulating head roll angle from surface images.

6. CONCLUSION

In this paper, we showed a new head positioning system that is compatible with radiation therapy used in head and neck cancer. We used soft actuators based on inflatable silicone membrane and helmet-like, 3D printed structure that allows patients to receive treatment with comfort (the open mask concept). We tested the properties of a single actuator at different pressure up to 14 psi while applying a humanoid head that has the same size and mass as a human head as a load. Preliminary angular displacement test (open loop) show that 5^0 to 7^0 was obtained within 0.4 sec when the pressure is varied from 7 to 14 psi. A vision based closed loop control was implemented in one of the designs (design 2) based on Recurrent Neural Network (RNN) using a Long Short Term Memory (LSTM) to operate in the presence of uncertainties and external disturbance. The new design (design 3) of the soft robot positioning system along with the closed loop control is expected to have significant clinical values and comfort for patients as well as cost effective solutions when fully developed.

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