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Recent Trends in Frameless and Mask Less Patient Motion Compensation in External Beam Radiation Therapy

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Abstract

Recently, frameless and mask less patient motion correction systems based on image-guided robot positioning have been proposed for patient motion compensation in radiation therapy. A majority of these works utilize rigid kinematic mechanisms for motion correction. However, these rigid mechanical components interfere with the therapeutic radiation beam. In addition, they share their complete workspace with the patient's body (risking safety), and their constant curvature components are hardly suitable for manipulating the soft tissues of the human body. In this report, we highlight some recent advancement that aim to stem these issues in our line of work: these systems utilize soft mechanisms for patient motion compensation in robotic radiation therapy. Essentially, we propose a soft parallel multi degree of freedom robot to counterbalance the currently prevalent rigid immobilization and patient motion correction mechanisms in head and neck external beam cancer therapy. This work is a key abridgment of recent developments in our mechanisms evolution. Within the bounds here set, this framework is intended to provide precise manipulation in lieu of the rigid platforms that are used today. Our goal is to edge open the door a little further towards in parallel soft actuation mechanisms that provide better patient comfort, radiation transparency, and precise immobilization.

Keywords: Robot • Therapeutic radiation • Cancer therapy

Introduction

Means of treating cancers may include one or a combination of drugs, radiation therapy, immunotherapy, stem cell transplant, targeted therapy, precision therapy, chemotherapy, or surgery.

Radiation Therapy (RT), sometimes in conjunction with surgery and chemotherapy, can be an invaluable single cancer treatment modality: it is very cost effective (accounting for only 5% of the total cost of cancer care [1] and its more effective given its advanced mode of radiation production and delivery.

By shaping the geometry of high energy radiation it allows radiation escalation to tumor targets while simultaneously sparing Organs-At-Risk (OARs).

The importance of RT is underscored by the fact that half of all cancer patients undergo RT treatment during the course of their illness; in fact, an estimated 40% of all curative cancer treatment modality are performed with RT [2].

Thus, because of its advanced radiation delivery method, RT is often the most suitable treatment modality for H and N cancers.

Literature Review

Robots in radiation therapy

In conventional high-energy RT, a non-static beam is used as a surgical instrument whereby the radiation source moves along primitive geometrical paths, irradiating the patient on a treatment couch in the process. Using rectangular fields, blocks, and wedges to specify flatness and symmetry, uniform radiation intensity can be produced [3]. In order to adaptively reposition the radiation beam during treatment, modern approaches utilize a six Degree of Freedom (DOF) robot arm to overcome the cross-sectional radiation delivery limitations of conventional systems. High-energy photons generated in a Linear Accelerator (LINAC) machine are aimed at tumor cells in the patient's body. To assure precision, LINAC is mounted on the end effector of an open kinematic chain robot arm. By this arrangement, the radiation beam can be delivered to the tumor target e.g. [4] within a patient lying in a supine position on a 6-DOF translational and rotatory robotic couch [5,6]. To conform the radiation to the tumor, minimize sustained damage to normal tissues, and ensure sparing of OARs during irradiation, in an inverse treatment planning process, multi-leaf collimator or MLCs are sequenced in order to

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conform the geometric field of the ionizing radiation into a non-uniform field [7]. Essentially, the MLCs conform the spatial localization of a high dose volume to a target volume.

Patient motion correction during RT

An open problem in radiosurgery is that of keeping the patient's position consistent with those in the pre-calculated treatment planning parameters. Studies have shown that serious changes do occur in delivered dose when a patient is slightly displaced or when there is a misalignment from the registered patient's pose angle. Ling et.al found that minute changes in couch angles affected target delivery results significantly more than accelerator angular changes. These uncertainties in couch translational and rotatory magnitudes may reduce the minimum target dose or increase the maximum spinal cord dose [8].

Therefore, in order to avoid dose miss, guarantee precision of dose delivery, assure repeatable positioning during inter-fractional treatments, as well as assure the efficacy of dose escalation to a target or minimize OARs' exposure to toxicity, a patient's position on the treatment couch should not fluctuate.

Limitations of rigid immobilization technologies

Currently, rigid frames and masks are prevalent in keeping the patient immobilized on the treatment machine (Figure 1).

Figure 1. Masks and frames for head immobilization.

Mask-based methods may employ thermoplastic masks (left inset of Figure 1), to secure the patient's head to the couch. However, this reduces immobilization accuracy owing to flex (producing a drift of up to 6 mm) and shrinkage over multiple uses. For deep tumors, masks are not suitable given the high sensitivity of rotational head motion; critical structures such as the brain stem and novel treatment modalities such as single isocenter multiple-target SRS make masks impractical.

Frame-based immobilization involves a metal ring screwed to the skull of the patient, then bolted to the treatment table right inset of Figure 1. The invasive nature and discomfort of the frame causes poor patient compliance to planned trajectory and reduces clinical efficacy. Even so, for certain patients frame placement is impossible given their unique cranial anatomy or prior surgical bone flaps; the frame limits the use of multiple RT delivery as patients cannot be subjected to daily attachment and removal of the frame. Setup errors between fractionated treatments (interfractional) or patient motion errors during a treatment session (intrafractional) often need to be corrected in real-time during treatment. Currently, the treatment is stopped, and the machine is recalibrated when the error is too large for this process to go on. The discomfort caused by head and neck masks and frames in prolonged treatment (i) can increase the voluntary and involuntary motion of patients; (ii) are time-consuming to calibrate on a treatment machine since doses are usually delivered in fractions over many weeks or months; (iii) lack real-time position correction of the patient's head motion; and (iv) have been known to cause patient discomfort after treatment.

Frameless and mask less immobilization

Frameless and Mask less (F and M) positioning systems are an emerging non-invasive immobilization technology in radiation therapy. They work without utilizing rigid masks and frames reducing side effects and optimizing patient comfort with little trade off in efficiency and effectiveness. The goal is to correct patient motion, ideally with a closed loop feedback controller implemented in real-time on a high precision robotic system improving the satisfaction of patients and clinicians, and maximizing dose delivered to a tumor whilst minimizing healthy tissues' exposure to radiation. Parallel robot configure rations have found good use along this research thrust. This is despite their higher number of actuated joints. In a way, this is an advantage because they distribute the weight of the load around the links of the robot, improving manipulation accuracy as a result; they also exhibit a desirable lightness property (albeit at the expense of a reduced workspace), and minimize the flexure torques that are otherwise common with open-loop kinematic chains. Thus, parallel kinematic configurations, in theory, enable greater precision with minimal control complications owing to the non-cumulative actuator errors [9].

Recent F and M research directions include the steel-cast assembled 4-DOF robot of [10] which corrected translational motion and a pitch rotational head motion; the HexaPOD parallel manipulator of [11] which utilized a system identification and a model predictive control approach to correct a tumor position on an Hexapod, or the in-house fabricated 6- DOF Stewart-Gough platform of [12]. However, these systems share common drawbacks e.g. Given their constant curvature end effectors/platforms, they are incapable of providing sophisticated manipulation e.g. for the inadvertent respiratory motions that often induce deviation from a target; being made out of rigid bodies, the attenuation of ionizing radiation dose has to be factored into treatment plans when these systems get commissioned. To improve the treatment planning process, these drawbacks need to be addressed. This would require the interdisciplinary effort of engineers, roboticists, physicists, and surgeons alike. In what follows, we present some of our work in soft robotic patient motion correction systems in RT [13-20].

System Description

We fabricate Circumferential Constrained and Radially Symmetric Elastomeric (CCOARSE) Fiber Reinforced Elastomeric Enclosures (FREE), henceforth called Inflatable Air Bladders (IABs). Inspired by the behavior of the skin papillae of certain cephalopods (bivalves, mollusks, octopus and cuttlefish) that change their smooth, planar physical texture into 3D textures up to a specific maximum size [21] in less than 3 seconds [22], we pattern our IABs similar to the skin papillae of these organisms where the elasticity of the skin papillae is controlled by a muscular hydrostatic mechanism: an elastomeric dermis antagonizes the muscle's fibers causing uniaxial shape erection.

CCOARSE-FREE IAB design

The soft actuator fabrication methodology is illustrated in Figure 2.

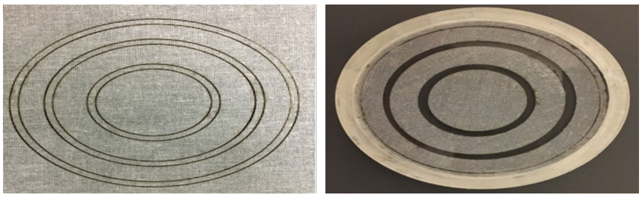

Figure 2. (L) Concentric circular patterns. (R) Fabric in uncured silicone.

We used 3-D printed molds to make an elastomeric membrane of width 3 4 mm and radius ≅ 50mm. To bear large deformations, we made the elastomeric membranes with Dragon Skin 10 (Smooth-On, Inc.), which have elongated properties of up to 1000% [23]. Given the low durometer hardness of Dragon Skin 10, Smooth-on Inc. (DS-10), it be- comes fragile under high air pressure. We thus reinforce the elastomer with thin-layered fabric (Fleishman Fabrics & Sup- plies, Philadelphia, PA). The fabric is anisotropic: exhibiting high extensibility in the axial direction and low extensibility in the radial direction on a spherical-polar plane, for example. This fabric inhibits over-expansion of the elastomer and concentrates force along the axial direction, as a result. The fabrication process proceeds as follows: (1) A thin layered fabric (Fleishman Fabrics and Supplies, Philadelphia, PA) is first laser cut into circular patterns; (2) The cut meshes are removed and laid onto uncured silicone (DS-10) which has been poured into the 3-D printed mold; (3) We then add a silicone topcoat layer to the fabric-elastomer matrix before we allow it to cure at room temperature.(4) For rubber materials, sealing is not leak-proof as it is with metal parts. Therefore, we seal the fiber-reinforced rubber material by clamping it between 3D-printed polylactic acid (PLA) holders similar to an O-ring to make the enclosure airtight. As seen in Figure 3.

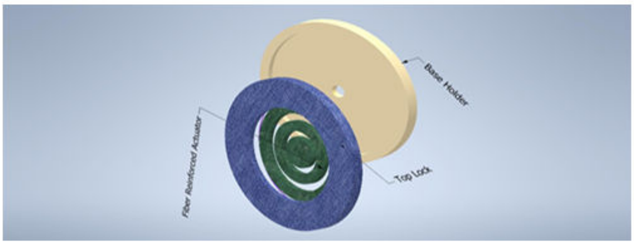

Figure 3. CCOARSE FREE assembly.

The circumference of the base part of the actuator locks into the PLA clamp at the bottom and by pressing the base from above and below, and fixing it with interspersed bolts at four points, the FREE is properly sealed while connected. (5) Compressed air can be passed through the pipe fitting connection into the enclosure as shown in the Figure 6 Nylon Phillips screws are used to further tighten the grip of the top clamp, the elastomeric-fiber matrix, and the bottom clamp so as to ensure that the enclosure is airtight.

The modules that comprise an actuator are connected to one another directly or through a spacer that connects rigid connecting elements. This fabrication method ensures that they can be easily adjoined, assembled or disassembled. As a result, the actuator is a little firm and well-fixated around a patient's cranial region. As our IABs are customized to create pathways for assembly tools to access the bolt heads, the developed assembly minimizes volume.

This sealing mechanism aids radiation transparency during radiation delivery to the head and neck region, an important requirement in robotic radiation therapy and stereotactic radiosurgery [24] where the immobilization mechanism must not attenuate dose radiation Figure 4 depicts the expected geometrical behavior of the IAB after deformation. The unique deformation pattern of the actuator is illustrated in Figure 4.

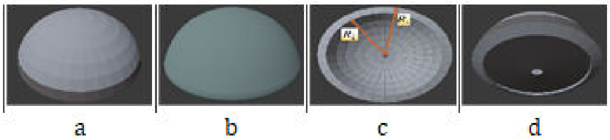

Figure 4. (a) Patterned layers, (b) Gaussian curvature at full deformation, (c) Hollow chamber with radii, {Ri, R◦}, (d) Back.

This deformation is similar to the way a balloon would stretch along its axial direction if a rope were tied around its circumference. Our proposed fabrication method allows users to rapidly iterate different designs with com- pressed low air pressure (at 3-15 psi), and it is advantageous because air is (i) cheaply available, (ii) environmentally-friendly, (iii) avoids electrical wirings, (iv) lightweight, and (v) in viscid. This aids a clean and safe human robot workspace suitable for medical robotics applications such as in emerging Magnetic Resonance Imaging Linas accelerators (MRI-Linacs).The experiments of Figure 5 illustrate the deformation of the IAB with two different designs (Figure 5).

Figure 5. Deformation of elastomer-only (left) and elastomeric-fabric matrix (right) under Low Air Pressurization (3-15psi).

The behavior at zero and full pressurization are indicated in each column. The top row shows the cured silicone without fabric while the bottom row shows the cured elastomer with the entrenched fiber matrix. As seen, the fiber free material exhibits a circumferential strain as well as radial strain while the fiber-constrained elastomer only exhibits a radial strain. As a result, we can generate a full Gaussian deformation and return to the reference planar configuration in 2, 3 seconds, similar to the spikes produced by the skin papillae of the Octopus. These quick Gaussian spikes are useful for rapid manipulation, and push, and release of the head when the actuators are interconnected as linkages to fit a kinematician's desired mechanisms. For example, the soft compliance and tensile strength of this silicone material make it well-suited for treatment procedures where non-magnetic and radiation-transparent components can boost stereotactic precision as well as improve tumor control in MRI-LINACs.

Discussion

Mechanism setup

Explorative robotic positioning research studies have demonstrated the feasibility of maintaining stable patient cranial motion consistent with treatment plans using rigid Stewart Gough platforms [10,12,25]. These achieve a 0.5 mm and 0.5° positioning accuracy 90% of the time. While aiding better clinical accuracy, they utilize rigid metallic components, electric motors and linear actuators which are not suitable for MRI imaging: they interfere with the magnets of the MRI machine, and can lead to patient fatality or significant damage to the MRI machine [26]. Time-resolved MRI techniques, which provide superior soft tissues image scans, can provide soft tissues delineation for use in brain or Head and Neck (H and N) Radiation Therapy (RT) [27-30]. Existing frame-based and frameless and mask less robotic motion correction mechanisms are not suitable for this because of their electro mechanical parts that introduce radiation attenuation and magnetic compliance concerns. We position IABs around the patient's cranium as illustrated in Figure 6.

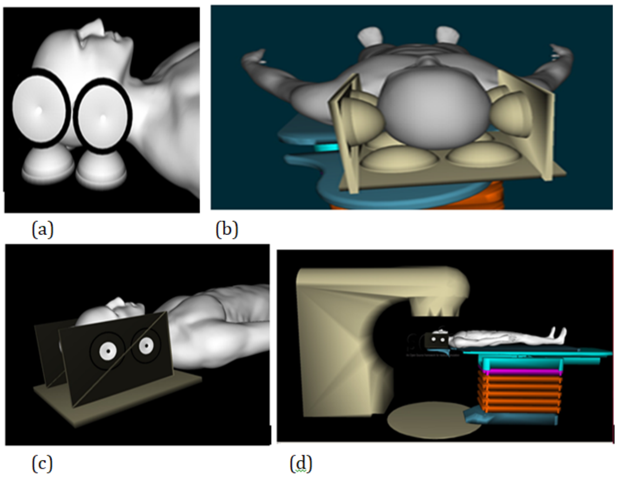

Figure 6. System setup. (a)Soft manipulators around pa- (b) Supine patient with side tient's cranium guides. (c) Radiation transparent carbon (d) Overall setup with gantry, nanotube IAB holder turntable and couch system.

The IABs are held in place around the head by a low-temperature rigid PVC foam insulation sheet, encased in carbon fiber to prevent radiation beam attenuation. Velcro stickers (not shown) hold the IABs in place. The freedoms provided by each IAB within the setup in Figure 6b are described as follows: the side actuators correct head motion along the left-right axis of the head anatomy, including the yaw and roll motions, while the base IABs correct the head motion along the anterior-posterior axis [31]. This arrangement offers prehensile manipulation via sensor-based motion manipulation strategies with flexible and electroelastic proprioceptive sensor plans i.e. the mechanical interactions of pushing or releasing by the IABs may be harnessed to further improve head manipulation robustness.

Conclusion

We have presented a summary of recent works in frame less and mask less radiation therapy, and their limitations. To counter radiation attenuation from electromechanical components utilized in current mechanisms, we have proposed a novel hardware mechanism for precise patient motion immobilization, which negates the characteristic patient discomfort, radiation attenuation, and immodularity.

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