BIOGRAPHICAL SKETCH

Provide the following information for the Senior/key personnel and other significant contributors.
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NAME: Olalekan P. Ogunmolu

eRA COMMONS USER NAME (credential, e.g., agency login): lakehanne

POSITION TITLE: Postdoctoral Researcher

EDUCATION/TRAINING *(Begin with baccalaureate or other initial professional education, such as nursing, include postdoctoral training and residency training if applicable. Add/delete rows as necessary.)*

INSTITUTION AND LOCATION	DEGREE *(if applicable)*	Completion Date MM/ YYYY	FIELD OF STUDY
The University of Sheffield, Sheffield, England	M.Sc (in Eng.)	11/2012	Control Systems
The University of Texas at Dallas, Richardson, TX	Ph.D	08/2019	Electrical Engineering (Robotics and Control Track)
The University of Chicago, Chicago, IL	Visiting Postdoc	09/2019	Radiation and Cellular Oncology
The University of Pennsylvania, Philadelphia, PA	Postdoc	Current	Radiation Oncology

A. Personal Statement

I am an interdisciplinary researcher who combines the elegance of control theory with the practical impact of robotics. The goal of my current research is to harness bleeding-edge control systems in modern robot configurations as substitutes for existing rigid mechanisms used in clinics today for patient motion management in stereotactic radiosurgery (SRS), brain as well as head-and-neck cancer radiation therapy. I recently started exploring the role of soft robots in integrated magnetic resonance imaging (MRI) and linear accerator (LINAC) for radiation therapy (RT). This is so as to improve the efficiency of modern radiation therapy cancer treatment outcomes. My goal with this proposal is to leverage the superior image scanning resolution and quality of magnetic resonance imaging (MRI) for feedback in managing the geometric uncertainties associated with modern treatment planning in RT. My robot designs leverage parallel configurations and radiation integrity/compliance for correcting head motion in closed-loop feedback SRS and head and neck cancer treatments.

Other than my applied engineering studies in clinical healthcare, I have made contributions to robust reinforcement learning by improving the transfer learning of learned control policies in real-time robot control deployments. I have also used deep learning architectures in the past to drastically improve the time it takes to find *near-optimal* solutions to the beam orientation optimization in intensity modulated radiation therapy. My control theory and robotics educational training along with the experience I have gathered in industry will be helpful in quickly realizing the objectives of my robotic radiosurgery and MRI integration goals in this proposal.

B. Positions and Honors

- **Research**

  2017 - 2019, Graduate Research Assistant, Medical Artificial Intelligence and Automation Laboratory, Division of Medical Physics and Engineering, UT Southwestern Medical Center.
  2017-2018, Research Assistant, Dr. Tyler Summers, Mechanical Engineering, UT Dallas.

2014 – 2019, Research Assistant, Electrical Engineering Department, University of Texas at Dallas.
2019 – Present, Postdoctoral Scholar, Department of Radiation Oncology, University of Pennsylvania
2018, Robotics Research Intern, Preferred Networks, Otemachi, Chiyoda-ku, Tokyo, Japan.
2016, Hardware Integration Intern, Amazon Robotics LLC, Summer.

- **<u>Teaching</u>**

  Adjunct Instructor, Robot manipulation, planning and control, Brandeis University, 2020 – Present

  Teaching Assistant, Introduction to Robotics, University of Texas at Dallas, 2014 – 2016

- **<u>Honors</u>**

  Google AI Travel and Conference Grant, October 2018
  IEEE RAS/IROS Travel Award (IROS 2018), August 2018
  Finalist at the 3rd Entrepreneurship Forum and Startup Competition, Sponsored by IEEE Robotics and Automation Society, KUKA AG, and Univ. Hamburg, August 2017
  NSF Doctoral Consortium Award (IROS 2017), August 2017
  Mary and Richard Templeton Graduate Fellowship, August 2017
  ROSCon Scholarship, (Open Software for Robotics Foundation), July 2017
  President's Teaching Excellence Award for Teaching Assistants, Nominated Feb. 2017
  Golden Key International Honour Society, Inducted Dec. 2016
  IEEE RAS/ISAM Travel Award (CASE 2016), August 2016
  Ericsson Graduate Fellowship, 2015 - 2016
  Jonsson Scholarship, 2014 - 2015
  Achievement Award, University of Florida (Declined), Fall 2014
  PTDF Overseas Scholarship Award, £25,500+ for one year, (~1.7% acceptance), 2011
  Federal Government (of Nigeria) Scholarship}, (~3.6% acceptance), 2002
  Ondo State (Nigeria) Scholarship, (~10% acceptance), 2004

- **<u>Professional Memberships And Services</u>**
  NYAS, The New York Academy of Sciences, Member. 2020-Present
  IEEE RAS, The IEEE Robotics and Automation Society, Member, 2017-Present
  AAPM, The American Association of Physicists in Medicine, Junior Member, 2020-Present
  ASTRO, The American Society for Radiation Oncology, Member, 2020-Present.

- **<u>Peer Reviewing Activities</u>**
  JBHI, An IEEE Journal of Biomedical and Health Informatics Access, 2019.
  External Grants Reviewer, AI for Species Discovery, National Geographic Society, 2019.
  Automatica, The International Federation of Automatic Control (IFAC), 2018, 2019.
  Access, IEEE Access Journal, 2017, 2018, 2019.
  NCAA, Springer's Neural Computing and Applications, 2017, 2018, 2019.
  ICML, International Conference on Machine Learning, 2017, 2020.
  CDC, IEEE International Conference on Decision and Control, 2018, 2019, 2020.
  DSCC, American Society of Mechanical Engineers (ASME) Dynamic Systems and Control Conference, 2017-Present.
  ICRA, IEEE International Conference on Robotics and Automation, Flagship IEEE Robotics and Automation Society Conference in the World, 2017-2020.
  IROS, IEEE/Robotics Society of Japan (RSJ) International Conference on Intelligent Robots and Systems, Flagship IEEE/RSJ Conference on Robotics, 2017-2020.
  ACC, IEEE American Control Conference, 2017, 2018, 2019.
  The IFAC World Congress, The International Federation of Automatic Control, A worldwide, interdisciplinary congress of scientists and engineers to share up-to-date, complete and universal view of control and analysis techniques, 2017, 2018.

C. Contributions to Science

Soft robotics is an emerging sub-specialty in the field of robotics which mitigates the difficulty of operating in unstructured, congested and nonlinear environments unlike their rigid robot counterparts. Inspired from the dynamics of living organisms such as muscular hydrostats (octopus and elephant trunks), and made out of artificial muscles and connective tissues, robots with a soft structure and delicate tissue have redundant degrees of freedom that are helpful in delicate control in cluttered or complex nonlinear dynamical systems. They have the potential to provide versatile adaptability and flexibility for an object’s movement, support or manipulation. My research capitalizes on soft robot designs to manipulate body parts during brain as awell as head and neck radiation therapy treatments of cancer tumors. To the best of my knowledge, I am the only researcher in the United states who undertakes this accurate patient positioning research challenge of addressing dose efficacy while guaranteeing patient comfort, eliminating dose attenuation and obtaining an AAPM task group approved accuracy requirement -- by using soft tissue materials to achieve these goals. By controlling the amount of fluid in the internal cavities of my soft robots, I have compensated motion deviation using non-parametric models derived from indirect adaptive control. My hardware design absorbs the reactive pressure from the patient's displacement during manipulation, thus guaranteeing patient's comfort. The radio-transparency of these soft robots to ionizing radiation make situating them close to the tumor source an attractive option for fast motion compensation -- mitigating against the inherent delay between the computation of control signals and actuation in rigid compensation works that have been proposed so far. My continuum, compliant and configurable (C3) inflatable air bladders (IABs) mitigate the highlighted issues that rigid robot compensation mechanisms and the state of the art Cyberknife system introduce. My soft elastomeric actuators provide therapeutic patient motion compensation during RT through inflation, deflation, extension or contraction governed by their material moduli, incompressibility or internal pressurization when given a reference trajectory.

Since soft robots are much cheaper to mass-produce compared to rigid robots, my platform reduces the cost of providing healthcare for cancer patients, and has the potential to spur other research directions in scaling composite models for real-time deployments in control systems: in space robotics, consumer robotics (warehouses) and democratize human-friendly robots in homes and society at large. I have responded to the challenges in my field by proposing a novel and precise position immobilization system using soft actuators that guarantees patient comfort, and dose efficacy and an efficient clinical outcome.

BIOGRAPHICAL SKETCH

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NAME: Rodney D. Wiersma

eRA COMMONS USER NAME (credential, e.g., agency login): RWIERSMA

POSITION TITLE: Associate Professor

EDUCATION/TRAINING *(Begin with baccalaureate or other initial professional education, such as nursing, include postdoctoral training and residency training if applicable. Add/delete rows as necessary.)*

INSTITUTION AND LOCATION	DEGREE *(if applicable)*	Completion Date MM/YYYY	FIELD OF STUDY
University of Alberta, Canada	B.Sc.	06/1999	Physics
Simon Fraser University, Canada	M.Sc.	06/2002	Physics
Max-Plank-Institute, Germany	Ph.D.	06/2006	Physics
Stanford University, USA	Postdoc	01/2009	Medical Physics

A. Personal Statement

My research is primary focused on image guidance radiation therapy (IGRT), treatment planning optimization, quality assurance (QA) systems, and the application of robotics to radiation therapy (RT). I have a successful track record in project leadership, teaching/mentoring, securing external funding, and translating research from the lab to the clinic. I hold several US patents, with two presently licensed to commercial companies, and I am a founder of a QA startup company that employs several fulltime people. In the proposed research we aim to explore the potential of using pencil beam scanning (PBS) proton therapy to deliver FLASH therapy and evaluate it in animal systems. Heavy particle FLASH would overcome many of the inherent difficulties of electron FLASH in terms of penetration depth allowing deep seated tumors to be treated. We have created a well-rounded team, where my expertise in robotics, optimization, and QA will complement the significant proton expertise of my colleagues. To implement PBS in our dedicated small animal research room, I will contribute to the development of a robotic based PBS system as well as a 6-degree-of-freedom treatment table for canine studies. In addition, I will be involved with FLASH treatment parameter optimization and the development of FLASH specific QA procedures.

B. Positions and Honors

Positions

2009-2011 Instructor, Radiation and Cellular Oncology, University of Chicago
2011-2019 Assistant Professor, Radiation and Cellular Oncology, University of Chicago
2019- Associate Professor, Radiation Oncology, University of Pennsylvania
2019- Director of Research, Physics, Radiation Oncology, University of Pennsylvania

Honors

1996-1999 Alberta Rutherford Scholarship for undergraduate studies
2002 Simon Fraser University graduate research award
2002-2006 Deutsche Promotionstipendium (German PhD Scholarship)
2004 Selected to attend 54th Nobel Laureates Meeting in Lindau, Germany
2007 ASTRO travel award
2010 Feature article Medical Physics Web, “Stereotactic Radiosurgery: Losing the Frame”.
2014 Feature article Medical Physics Web, “Combined MV+kV planning enables real-time tracking”.
2015 The Kurt Rossmann Award for Excellence in graduate medical physics teaching

2017 Medical Physics Journal Editor's Choice, "Use of Proximal Operator Graph Solver for Radiation Therapy Inverse Treatment Planning"

Other Experience and Professional Memberships

2006- Member, American Association of Physicists in Medicine (AAPM)
2009- State of Illinois IEMA Division of Nuclear Safety
2010- American Board of Radiology (DABR) in Therapeutic Radiologic Physics
2010- American Cancer Society grant reviewer for Epidemiology and Clinical Research

C. Contributions to Science

Use of robotic systems in radiation therapy

I was the first to develop a method for performing real-time patient head motion cancellation in frameless stereotactic radiosurgery (SRS). Currently, to achieve the 1-2 mm precision for intracranial SRS, a metal head ring is rigidly fixated to the patient's skull using screws under local anesthesia, and then bolted on the treatment couch. The discomfort, inconvenience, and invasive nature associated with the frame preparation have been identified as the main cause of poor patient compliance and poor clinical efficiencies when SRS is medically indicated. Frameless SRS methods based on a thermoplastic mask placed over the face and fixed to the couch has been reported to limit head motion to approximately 2 - 3 mm due to rotation about the fulcrum at the back of the skull. My group is working to develop a frameless and maskless SRS technique that uses real-time 6DOF optical tracking together with a 6DOF robotic head stage for cancellation of patient head motion. This approach has the potential to be less invasive than current frameless SRS techniques while still achieving accuracies better or equal than traditional frame based SRS.

1. Belcher AH, Liu X, Chmura S, Yenice K, Wiersma RD. Towards frameless maskless SRS through real-time 6DoF robotic motion compensation. Physics in Medicine & Biology. 2017 Nov 13;62(23):9054
2. Wiersma RD, Wen Z, Sadinski M, Farrey K, Yenice KM. Development of a frameless stereotactic radiosurgery system based on real-time 6D position monitoring and adaptive head motion compensation. Physics in medicine and biology. 2009 Dec 17;55(2):389
3. Kang HJ, Grelewicz Z, Wiersma RD. Development of an automated region of interest selection method for 3D surface monitoring of head motion. Medical physics. 2012 Jun 1;39(6):3270-82
4. Liu X, Belcher AH, Grelewicz Z, Wiersma RD. Robotic real-time translational and rotational head motion correction during frameless stereotactic radiosurgery. Med Phys. 2015 Jun;42(6):2757-63.

Image-guided radiation therapy and treatment planning optimization

I was the first to develop the combined MV+kV imaging technique for the purpose of performing real-time 3D tumor tracking during radiation therapy. This method is particularly suited to modern LINACs which come pre-equipped with onboard MV and kV imaging devices arranged orthogonally on the gantry. This orthogonal geometric arrangement offers a natural stereoscopic pair, and thus can be used for 3D tumor position monitoring. The MV-kV tracking method has also been verified to operate successfully on next generation volumetric modulated arc therapy (VMAT). I am also the primary inventor of the combined MV+kV treatment planning approach which allows optimal incorporation of the kV dose into the MV treatment plan.

1. Wiersma RD, Mao W, Xing L. Combined kV and MV imaging for real-time tracking of implanted fiducial markers. Medical physics. 2008 Apr 1;35(4):1191-8
2. Liu W, Wiersma RD, Mao W, Luxton G, Xing L. Real-time 3D internal marker tracking during arc radiotherapy by the use of combined MV–kV imaging. Physics in medicine and biology. 2008 Nov 28;53(24):7197
3. Wiersma RD, Riaz N, Dieterich S, Suh Y, Xing L. Use of MV and kV imager correlation for maintaining continuous real-time 3D internal marker tracking during beam interruptions. Physics in medicine and biology. 2008 Dec 5;54(1):89
4. Grelewicz Z, Wiersma RD. Combined MV+ kV inverse treatment planning for optimal kV dose incorporation in IGRT. Physics in medicine and biology. 2014 Mar 10;59(7):1607

Quality assurance methods for modern radiation therapy

I have been actively involved in improving patient safety in radiation therapy (RT) through the development of several modern quality assurance (QA) methods. Success of RT critically depends on the proper function of many complex devices such as linear accelerators (LINAC), computer tomography (CT), magnetic resonance imaging (MRI), positron emission tomography (PET), and high dose bracytherapy (HDR). Clinically, an adequate confidence that these devices will satisfy the given requirements for quality is achieved by performing QA consisting of a series of planned and systematic actions (ISO 9000:1994). QA reduces uncertainties and errors in dosimetry, equipment performance, treatment delivery, etc., thereby improving dosimetric and geometric accuracy and the precision of dose delivery. Clinically, this improvement is translated into enhanced tumor control as well as reduced complication and likelihood of accidents and errors occurring. Here I have developed QA methods that allow for high temporal resolution tests of radiation beam gating cycles, 6D phantoms for performing LINAC QA, and tests for both EPID and optical patient motion tracking devices.

1. Wiersma RD, Tomarken SL, Grelewicz Z, Belcher AH, Kang H. Spatial and temporal performance of 3D optical surface imaging for real-time head position tracking. Medical physics. 2013 Nov 1;40(11)
2. Wiersma RD, Xing L. Examination of geometric and dosimetric accuracies of gated step-and-shoot intensity modulated radiation therapy. Medical physics. 2007 Oct 1;34(10):3962-70
3. Belcher AH, Liu X, Grelewicz Z, Pearson E, Wiersma RD. Development of a 6DOF robotic motion phantom for radiation therapy. Medical physics. 2014 Dec 1;41(12)
4. Wiersma RD, McCabe BP, Belcher AH, Jensen PJ, Smith B, Aydogan B. High temporal resolution characterization of gating response time. Medical physics. 2016 Jun 1;43(6):2802-6

Complete List of Published Work in My Bibliography
http://www.ncbi.nlm.nih.gov/sites/myncbi/1rAZJDFGA9Ckq/bibliography/49466503/public/?sort=date&direction=descending

D. Additional Information: Research Support and/or Scholastic Performance
Ongoing research support

NIH-R21 1R21EB028103-01 Wiersma (co-PI) 06/01/2019 - 05/31/2021
Enhanced megavoltage imaging for radiotherapy by light-field imaging of scintillators: we propose to overcome the EPID contrast obstacle by increasing the photon detection layer to 10-50mm using a transparent scintillator and then capturing its 4D light field using a specially designed optical camera system.

NIH-R01 1R01CA227124-01A1 Wiersma (PI) 12/04/2018 - 11/30/2023
Development of a portable and compact robotic system for frameless and maskless stereotactic radiosurgery: the goal of this project is to design, construct, and implement a robotic SRS system for early clinical trials on brain cancer patients.

Completed Research Support

American Cancer Society RSG-13-313-01-CCE Wiersma (PI) 07/01/2013 - 06/30/2018
Frameless SRS based on robotic motion cancellation: to develop a next generation frameless maskless SRS approach where small intrinsic patient head motions are continuously cancelled out during frameless SRS treatment.

CTSA-Institute for Translational Medicine Wiersma (PI) 06/01/2016 - 06/01/2017
Genetically modified bacteria for transport and synthesis of iron oxide nanoparticles at the tumor site: creation of tumor targeting bacteria containing iron oxide for hyperthermia therapy purposes.

BIOGRAPHICAL SKETCH

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NAME: Turner, Kevin T.

eRA COMMONS USER NAME (credential, e.g., agency login): KEVINTTURNER

POSITION TITLE: Professor and Chair, Mechanical Engineering and Applied Mechanics, The University of Pennsylvania

EDUCATION/TRAINING *(Begin with baccalaureate or other initial professional education, such as nursing, include postdoctoral training and residency training if applicable. Add/delete rows as necessary.)*

INSTITUTION AND LOCATION	DEGREE *(if applicable)*	Completion Date MM/YYYY	FIELD OF STUDY
Johns Hopkins University	B.S	05/1999	Mechanical Engineering
Massachusetts Institute of Technology	M.S	05/2001	Mechanical Engineering
Massachusetts Institute of Technology	Ph.D	05/2004	Mechanical Engineering
Massachusetts Institute of Technology	Postdoctoral	08/2005	Materials Science and Engineering

A. Personal Statement

My research addresses fundamental and applied problems at the intersection of the fields of surface and interface mechanics and micro- and nanosystems. Surface and interface mechanics, which encompasses fracture, contact, and adhesion mechanics, plays a crucial role in determining the behavior of many micro- and nano-scale systems and manufacturing processes. My research group uses a combination of experimental measurements, analytical modeling, and numerical simulations to improve and realize innovative micro- and nanomanufacturing processes as well as to develop new approaches to measure the mechanical properties of interfaces at small scales. My current work includes projects in nanocomposites, materials with tunable adhesive properties, and flexible electronics.

The proposed project includes development of soft mechanical sensors. I will leverage my expertise in sensors, mechanics of materials, and flexible electronics in my mentoring role on the proposed project.

B. Positions and Honors

<u>Position and Employment</u>

1999-2004 Research Assistant, Massachusetts Institute of Technology, Cambridge, MA
2004-2005 Postdoctoral Associate and Lecturer, Department of Materials Science and Engineering, Massachusetts Institute of Technology, Cambridge, MA
2005-2011 Assistant Professor of Mechanical Engineering, University of Wisconsin, Madison, WI
2006-2011 Faculty Affiliate, Materials Science Program, University of Wisconsin, Madison, WI
2007-2011 Faculty Affiliate, Biomedical Engineering, University of Wisconsin, Madison, WI
2011-2011 Associate Professor of Mechanical Engineering, University of Wisconsin, Madison, WI
2011-present co-Founder, systeMECH, Inc, Madison, WI
2011-2016 Associate Professor of Mechanical Engineering and Applied Mechanics (primary) and Materials Science and Engineering (secondary) University of Pennsylvania, Philadelphia, PA
2012-2017 Director, Quattrone (Wolf) Nanofabrication Facility, University of Pennsylvania
2016-2019 Graduate Group Chair, Mechanical Engineering & Applied Mechanics, University of Pennsylvania
2019-present Chair, Mechanical Engineering & Applied Mechanics, University of Pennsylvania

Memberships

1998-present Member, American Society of Mechanical Engineering
2000-present Member, Materials Research Society
2008-present Member, Adhesion Society

Honors

2008	ASEE Ferdinand P. Beer and E. Russell Johnston, Jr. Outstanding New Mechanics Educator
2009	National Science Foundation CAREER Award
2009	3M Non-tenured Faculty Award
2009	R&D 100 Award for UNCD AFM probes
2011	Young Adhesion Scientist Award, the Adhesion Society
2011	Outstanding Young Manufacturing Engineer Award, the Society of Manufacturing Engineers
2012	NAE Frontiers of Engineering Symposium, invited participant
2014	ASME Sia Nemat-Nasser Early Career Award

C. Contribution to Science

1. Microelectronic and microelectromechanical devices need to have robust and stable performance over long service lives. The performance of these devices hinge critically on the mechanical properties of the materials and interfaces formed during the fabrication process. Thus, characterization of the mechanical properties of devices and materials after fabrication is critical. Turner has developed and implemented numerous small-scale mechanical testing to interrogate mechanical properties in fabricated devices. Because of the size of the devices and features, innovative mechanical testing and modeling techniques are often required. Examples of such work are included in the following publications.

    a. Grierson DS, Liu J, Carpick RW, and **Turner KT** (2013) Adhesion of nanoscale asperities with power-law profiles, *Journal of Mechanics and Physics of Solids*, 61: 597-610.
    b. Wald MJ, Considine JM, and **Turner KT** (2013) Determining the Elastic Modulus of Compliant Thin Films Supported on Substrates from Flat Punch Indentation Measurements," *Experimental Mechanics,* 53: 931-41.
    c. Cavallo F, Grierson DS, **Turner KT**, and Lagally MG (2011) "Soft Si": Effective stiffness of supported crystalline nanomembranes, *ACS Nano*, 5: 5400-7.
    d. Tadepalli R and **Turner KT** (2008) A chevron specimen for the measurement of mixed-mode interface toughness of wafer bonds, *Engineering Fracture Mechanics*, 75: 1310-19.

2. Wear of materials is a ubiquitous problem that limits the performance of many systems, ranging from bearings to microscale devices to biomechanical joints. Wear is a significant issue that limits the lifetime of atomic force microscope probes in nanometrology and nanofabrication processes. Turner, in collaboration with others, has investigated the wear of atomic force microscope probes at the nanoscale and developed new understanding of the mechanisms of wear. Specifically, the papers below show and atom-by-atom attrition process with a rate that increases with applied stress.

    a. Vahdat V, Ryan KE, Keating PL, Jiang Y, Adiga SP, Schall JD, **Turner KT**, Harrison JA, and Carpick RW (2014) Atomic-scale wear of amorphous hydrogenated carbon during intermittent contact: a combined study using experiment, simulation, and theory, *ACS Nano*, 8: 7027-40.
    b. Vahdat V, Grierson DS, **Turner KT**, and Carpick RW (2013) Mechanics of interaction and atomic-scale wear of amplitude modulation atomic force microscopy probes, *ACS Nano*, 7: 3221-35.
    c. Liu J, Grierson DS, Moldovan N, Notbohm J, Li S, Jaroenapibal P, O'Connor SD, Sumant AV, Neelakantan N, Carlisle JA, **Turner KT**, Carpick RW (2010) Preventing nanoscale wear of atomic force microscopy tips through the use of monolithic ultrananocrystalline diamond probes, *Small*, 6: 1140-49.
    d. Liu J, Notbohm J, Carpick RW, and **Turner KT** (2010) Method for characterizing nanoscale wear of atomic force microscope tips, *ACS Nano*, 4: 3763-72.

Complete List of Published Work in MyBibliography:

http://turner.seas.upenn.edu/publications.htm

D. Research Support

Current Research Projects

NSF 1542153 (PI: M. Allen) 09/01/15-08/31/20
NNCI: Mid-Atlantic Nanotechnology Hub (MANTH) for Research, Education, & Innovation
The goal of this award is to make nanotechnology infrastructure at the University of Pennsylvania broadly available to academic and industrial users in the mid-Atlantic region.
Role: co-Principal Investigator

NIH/NIAMS R01 AR071718 (PI: X. Liu) 04/01/17-03/31/22
Effects of reproduction and lactation on postmenopausal bone health
The major goals of this project are to identify the critical phenotypic bone structure, material properties, and mechano-sensitivity resulting from reproduction and lactation that protect the maternal skeleton from future postmenopausal bone loss.
Role: Senior personnel

NSF 1663037 (PI: K. Turner) 04/01/17-03/31/21
Collaborative Research: Exploiting tunable stiffness for dynamic adhesion control at the macro- and micro-scale
The major goal of this project is to exploit materials with tunable stiffness to realize surfaces with dynamic and switchable adhesion properties.
Role: Principal Investigator

U.S. Endowment for Forestry & Communities, Inc (PI: K. Turner) 05/01/17 – 09/30/20
3D Printing of Cellulose Nanofibril Materials
The major goal of this proposal is to investigate the fabrication of bulk nanocellulose parts via additive manufacturing (i.e. 3D printing) techniques.
Role: Principal Investigator

NSF 1662695 (PI: D. Lee) 06/01/17-03/31/21
Nanostructured Composite Coatings to Harden and Toughen Polymer Surfaces
The major goal of this project is to investigate the processing, structure, property relationships of nanoparticle composite films synthesized through capillary rise infiltration.
Role: co-Principal Investigator

USDA/NIFA 2016-08810 (PI: K. Turner) 07/01/17-06/30/20
Engineering Cellulose Nanomaterials with High Toughness
The major goal of this project is to investigate the toughness and crack growth resistance of materials based cellulose nanomaterials.
Role: Principal Investigator

NSF 1720530 (PI: A. Yodh) 09/01/17-08/31/23
Materials Research Science and Engineering Center (MRSEC)
The major goal of Turner’s work in this center is to examine the mechanics and fracture of disorded solids, including molecular glasses and nanoparticle films.
Role: Senior Personnel

NSF 1761726 (PI: J. Bassani) 04/01/18-03/31/21
Tailoring interface geometry to realize controlled and directionally-dependent adhesion
The major goal of this project is to investigate strategies to tailor the interface toughness (fracture resistance) through micro- and nano-patterning.

Role: co-Principal Investigator

NSF 1830475 (PI: K. Turner) 09/01/18 – 08/31/21
NRI:INT:COLLAB: Soft Active Contact Pads with Tunable Stiffness and Adhesion for Customizable Robotic Grasping
The major goal of this project is to develop robotic gripping strategies based on materials with tunable stiffness.
Role: Principal Investigator

Past Research Projects (<3 years old)

NSF 1435745 (PI: Turner) 09/01/2014-08/31/2018
Structured Composite Materials with Variable Adhesion Properties
This grant supports the design, fabrication, and characterization of novel micro- and nano-structured surfaces with tunable adhesion.
Role: Principle Investigator

BIOGRAPHICAL SKETCH

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NAME: James H. Pikul

eRA COMMONS USER NAME (credential, e.g., agency login): PIKULJ
POSITION TITLE: Assistant Professor, Mechanical Engineering and Applied Mechanics, The University of Pennsylvania

EDUCATION/TRAINING *(Begin with baccalaureate or other initial professional education, such as nursing, include postdoctoral training and residency training if applicable. Add/delete rows as necessary.)*

INSTITUTION AND LOCATION	DEGREE *(if applicable)*	Completion Date MM/YYYY	FIELD OF STUDY
University of Illinois at Urbana-Champaign	PhD	2015	Mechanical Engineering
University of Illinois at Urbana-Champaign	MS	2011	Mechanical Engineering
University of Illinois at Urbana-Champaign	BS	2009	Mechanical Engineering

A. Personal Statement

I have the expertise, leadership, training, and motivation necessary to successfully mentor Olalekan Ogunmolu for his K99 fellowship. I am a mechanical engineer with expertise in materials engineering, micro and nanoscale fabrication, soft robotics, and electrochemistry. My group combines these expertise to enable new robotic capabilities. This is demonstrated by my recent publication in *Science*[1], which presents a new physical approach for controlling the shape transformation of stretchable material surfaces, in an engineered system that provides reversible actuation, fast response, large forces, geometric and sequential control, and ease of fabrication. I also have expertise in electrochemistry, which I have used to improve the mobility of robots[2], to make the world's most power dense batteries[3], and realize the first room-temperature healing of metal[4]. I have also led many projects, including several $1,000,000 plus projects sponsored by NSF and DARPA. I will use this expertise to mentor Olalekan in science, leadership, and management throughout his project.

1. James H. Pikul, Shuo Li, Hedan Bai, Roger T. Hanlon, Itai Cohen, Robert F. Shepherd, "Stretchable surfaces with programmable 3-D texture morphing for synthetic camouflaging skins", *Science*, vol. 358, pp. 210-214, October 18, 2017.

2. Cameron A. Aubin, Snehashis Choudhury, Rhiannon Jerch, Lynden A. Archer, James H. Pikul, Robert F. Shepherd, "Electrolytic Vascular Systems for Energy Dense Robots", *Nature*, 1, June, 2019.

3. James H. Pikul, Huigang Zhang, Jiung Cho, Paul V. Braun, and William P. King, "High power lithium ion micro batteries from interdigitated three-dimensional bicontinuous nanoporous electrodes", *Nature Communications*, vol. 4, pp. 1732, 2013

4. Zakaria Hsain, James H. Pikul, "Low-energy Room-temperature Healing of Cellular Metals", *Advanced Functional Materials*, pp. 1905631, August 2019.

B. Positions and Honors

Positions

2017 – Present	Assistant Professor	University of Pennsylvania
2015 – 2017	Postdoctoral associate	Cornell University

Honors

2020 Moore Inventor Fellow through the Gordon and Betty Moore Foundation
2019 Best Paper Award at The 19th International Conference on Micro and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS), Krakow, 2019
2019 NSF CAREER award in ECCS - CCSS
2019 Scialog Fellow through the Research Corporation for Science Advancement - Advanced Energy Storage
2019 Office of Naval Research Young Investigator Award
2013 Materials Research Society Gold Award

C. Contributions to Science

1. Control and mobility of soft robotics

Technologies using soft, stretchable materials are increasingly important, yet we are unable to control how they stretch with much more sophistication than inflating balloons. Nature, however, demonstrates remarkable control of stretchable surfaces: for example, cephalopods can project hierarchical structures from their skin in milliseconds for a wide range of textural camouflage, run across the ocean floor, change color, and hydrojet at high speeds through the ocean. Inspired by nature, I have developed theoretical and experimental techniques that enable the design, fabrication, and control of soft robotics. I have pioneered shape control of soft, stretchable materials by prescribing strain in inflated and expanded 2-D surfaces. My combined theoretical and experimental work has led to state-of-the-art capabilities for controlling the shape of soft surfaces that deform into complex shapes. I have also demonstrated the use of flow battery chemistries to increase the energy density of machines, vehicles, and robots by adding energy storage functionality into existing fluidic actuators. This improves the energy density of the robot by more than 4X. I have received an NSF CAREER award for this work.

A. James H. Pikul, Shuo Li, Hedan Bai, Roger T. Hanlon, Itai Cohen, Robert F. Shepherd, "Stretchable surfaces with programmable 3-D texture morphing for synthetic camouflaging skins", *Science*, vol. 358, pp. 210-214, October 18, 2017.

B. Steven Ceron, Itai Cohen, Robert F. Shepherd, James H. Pikul, Cindy Harnett, "Fiber Embroidery of Self-Sensing Soft Actuators", *Biomimetics*, vol. 3, September 2018.

C. Cameron A. Aubin, Snehashis Choudhury, Rhiannon Jerch, Lynden A. Archer, James H. Pikul, Robert F. Shepherd, "Electrolytic Vascular Systems for Energy Dense Robots", *Nature*, 1, June, 2019.

D. T.J. Wallin, J.H. Pikul, S. Bodkhe, B.N. Peele, B.C. Mac Murray, D. Therriault, B.W. McEnerney, R.P. Dillon, E.P. Giannelis, R.F. Shepherd, "Click chemistry stereolithography for soft robots that self-heal", *Journal of Materials Chemistry B*, vol. 5, pp. 6249-6255, 2017.

2. Energy storage with increased energy and power

In my research group, we seek to realize new battery architectures that enhanced battery performance or enable entirely new functionality. Metal-air batteries offer higher energy densities that lithium ion batteries. We have recently expanded the architectural advantage of metal-air batteries by demonstrating the ability to electrochemically extract energy from external metal surfaces using a metal-air scavenger (MAS) composed of a hydrogel electrolyte connected to a cathode current collector. This new approach can power microelectronics and cm scale robotic devices that operate on or near metal surfaces. The effective energy density of the metal-air scavenger was 2.3 times greater than prior metal-air batteries and 12.7 times greater than commercial lithium-ion batteries. This work is being funded through an ONR-YIP. There is also increasing need for higher performance microbatteries due to the increased growth of internet-connected devices (125 billion by 2030) and micro-robotics. I have been a global leader in developing high performance microbatteries for the last 8 years, and my group is continuing to make significant strides in this area. My prior work showed that we could make microbatteries with the power density of supercapacitors, 1,000 times higher than the power density of commercial batteries. Current work in my lab is focused on three funded DARPA SHort-Range Independent Microrobotic Platforms projects. I am the PI on one and co-PI on the other two. The goal of these projects is to realize novel energy storage technologies for microrobots.

A. Min Wang, Unnati Joshi, James H. Pikul, "Powering electronics by scavenging energy from external metals" *ACS Energy Letters*, 2020

B. James H. Pikul, Paul V. Braun, William P. King, "Performance modeling and design of ultra-high power microbatteries", *Journal of the Electrochemical Society*, vol. 164.11, pp. E3122-E3131, 2017.

C. Hailong Ning, James H. Pikul, Runyu Zhang, Xuejiao Li, Sheng Xu, Junjie Wang, John A. Rogers, William Paul King, and Paul V. Braun, " Holographic Patterning of High Performance on-chip 3D Lithium-ion Microbatteries", *Proceeding of the National Academy of Sciences*, vol. 112, no. 21, pp. 6573-6578, 2015.

D. James H. Pikul, Huigang Zhang, Jiung Cho, Paul V. Braun, and William P. King, "High power lithium ion micro batteries from interdigitated three-dimensional bicontinuous nanoporous electrodes", *Nature Communications*, vol. 4, pp. 1732, 2013

3. <u>Multifunctional Materials</u>

My lab's work on multifunctional materials is inspired by the complex functionalities in natural materials (like self-healing fractures in bone) and the incredible benefit similar functionalities would offer to engineered systems. We use modern engineering and design principles to realize new synthetic materials with mechanical and chemical properties not available in natural or man-made materials. In one project, we have combined new models of nanoscale self-assembly with electrochemical deposition to realize high-strength and light-weight metals. I recently published work showing that these materials (with 200-500 nm pore sizes) could achieve the strength of titanium and the density of water. My group has also demonstrated rapid, effective, low-energy, and room-temperature healing of metallic materials by using electrochemistry and polymer-coated cellular nickel to mimic the transport-mediated healing of bone. This is the first room temperature healing of metals since humans have first used metals 6,000 years ago.

A. James H. Pikul**,** Sezer Özerinç, Burigede Liu, Runyu Zhang, Paul V. Braun, Vikram S. Deshpande, William P. King, " High strength metallic wood from nanostructured nickel inverse opal materials", *Scientific Reports*, 9.1, 2019.

B. James H. Pikul, Paul V. Braun, and William P. King, "Micromechanical devices with controllable stiffness fabricated from regular 3D porous materials", *Journal of Micromechanics and Microengineering*, vol. 24, 105006, 2014

C. Zakaria Hsain, James H. Pikul, "Low-energy Room-temperature Healing of Cellular Metals", *Advanced Functional Materials*, pp. 1905631, August 2019.

D. Additional Information: Research Support and/or Scholastic Performance

Ongoing Research Support

DARPA: PI

"Electrochemical deposition of thick and continuous electrodes for high voltage and energy density lithium metal microbatteries"

- Co-PI are Paul Braun (University of Illinois at Urbana-Champaign) and John Cook (Xerion Advanced Battery Corp.)
- 03-01-2019 to 02-28-2022

Office of Naval Research Young Investigator Program: PI

"Understanding electrochemically induced surface evolution and transport at metal-hydrogel interfaces for metal-air scavenger power sources"

- 04-15-2019 to 04-14-2022

NSF: PI

"EFRI C3 SoRo: 3-D surface control for object manipulation with stretchable Materials"

- Co-PIs are Michael Posa, Mark Yim, Chris Santangelo (U. Mass – Amherst), Ryan Hayward (U. Mass – Amherst)
- 01-01-2020 to 12-31-2023

NSF: PI

"MRSEC: Surface Evolution of Dealloyed Mesoporous Metals for Oxygen Metals for Oxygen Reduction Catalysts in Metal-Air Battery and Fuel Cell Electrodes"

- Co-PI are Eric Detsi (MSE) and Eric Stach (MSE)
- 09-01-2018 to 08-31-2020

NSF CAREER: PI

"CAREER: Power and information transmission kinetics in multifunctional electrolytic vascular systems"

- 02-01-2020 to 01-31-2025

DARPA: co-PI

"Integrated High Voltage Battery and Magnetic Conversion Micropower Systems for Efficient Power Delivery to Microbiotic Actuators"

- PI is Mark Allen, Co-PI is Sue Bidstrup-Allen
- 03-01-2019 to 02-28-2022

Completed Research Support

None

Title:

K99 Year 1-2 4/1/21-3/31/23									
Personnel	**Role**	**Effort**	**Salary Yr 1**	**Salary Yr 2**	**%Salary requested**	**YR1 (plus Ebs)**	**%Salary requested**	**YR2 (plus Ebs)**	**Total 2 year period**
Lekan Molu	PI	100%	51,504	53,049	51,504	56,139	53,049	57,824	**113,963**
Rodney Wiersma	Mentor, Radiation Oncology (K99 & R00 Aims)								
George Pappas	Co-Mentor, Optimal control (Aim II)								
James Pikul	Co-Mentor, Hardware design (Aims I & III)								
Kevin Turner	Co-Mentor, Material Mechanics (Aims I & III)								
8.9% EB rate									
Total Personnel						**56,139**		**57,824**	**113,963**
Equipment									
Proportional Solenoid Valves						**3000**			
Venturi Pumps						**1240**			
Universal Laser Cutting Machine						**7,500**			
Travel									
Conference and Talks						**5,000**		**5,000**	**10,000**
Open access publications						**4,000**		**4,000**	**8,000**
Supplies									
Silicone Materials						**197**			**197**
Pressure Transducers						**929.64**			
Low-Temperature PVC Foams						**300**			
Miscellaneous						**1500**			
Load Cell and Displacement Sensors						**2750**			
Handheld Corona						**2000**			
Personnel fittings, hose connectors, miscellaneous etc						**3500**			
Other Expenses									**0**
Postdoc Health Insurance						**7,800**		**8,034**	**15,834**
Total Direct Costs						**95,856**		**74,858**	**170,714**
MTDC Base						**95,856**		**74,858**	**170,714**
F&A Costs	8%					**7,668**		**5,989**	**13,657**
Total Costs						**103,525**		**80,846**	**184,371**
research expenses not to exceed $30K						-9,717		12,966	
						11176.64			

Title:

R00 Year 1-3 4/1/2023-3/31/2026

Personnel	Role	Effort	Salary Yr 3	Salary Yr 4	Salary Yr 5	%Salary requested	YR3 (plus Ebs)	%Salary requested	YR4 (plus Ebs)	%Salary requested	YR5 (plus Ebs)		Total 3 year period
Lekan Molu	PI	100%	110,000	110,000	113,300	110,000	143,550	110,000	143,550	113,300	147,857		**434,957**
Total Personnel							**143,550**		**143,550**		**147,857**		**434,957**
Equipment													
3D Printing Machine			6,500										**0**
Travel													
Conference & Travel			5,500	5,500	5,500								**0**
Supplies													
													0
													0
													0
Other Expenses													
Publication Expenses			4000	4000	4000								**0**
Total Direct Costs							**143,550**		**143,550**		**147,857**		**434,957**
MTDC Base							**143,550**		**143,550**		**147,857**		**434,957**
F&A Costs	61%						**87,566**		**87,566**		**90,192**		**265,323**
Total Costs			126000	119500	122800		**231,116**		**231,116**		**238,049**		**700,280**
					over/under		17,885		17,885		10,951		

1 Budget Justification

Olalekan Ogunmolu, PhD, ***Principal Investigator, 12-month calendar year effort:*** Dr. Ogunmolu is a control systems engineer and roboticist by training. He also has medical physics experience in the areas of treatment planning and patient head motion correction in cancer RT. Prior to joining the University of Pennsylvania in Philadelphia as a postdoctoral fellow, he was a visiting postdoctoral scholar at the University of Chicagos Pritzker School of Medicine. Dr. Ogunmolu has many years of experience in hardware design, software architecture, system synthesis, and project management. Dr. Ogunmolu will develop the pneumatic hardware, integrate it with the electronic controllers, as well as write the motion planning software for this project. He will frequently consult with his co-mentors in order to address the aims proposed in K99 aims I-III and the R00 aim. Finally, Dr. Ogunmolu will be responsible for overall supervision of this project and collaboration with other experiments and testing procedures.

1.1 Mentored Phase, 2 years

Apart from salary support, many of the research-related costs of the project during the mentored phase will be subsidized by the research facilities and supplies already available in the labs of the mentors, Drs. Rodney Wiersma, James Pikul, and Kevin Turner.

1.1.1 Personnel: Olalekan Ogunmolu, PhD, Principal Investigator

A total of $113,963 is required for salary support for Dr. Olalekan Ogunmolu during the mentored phase (2 years). Year 1: $56,139; Year 2: 57,824.

1.1.2 Other Expenses

Postdoc health insurance is requested based on the University of Pennsylvania published rates for FY21. A total of $15,834 is requested for Dr. Ogunmolus postdoc health insurance for two years: $7,800 in the first year and $8,034 in the second year.

1.1.3 Equipment

- $3,000 Proportional Solenoid Valves (12 at $250 each from Dakota Instruments) to regulate air flow in and out of the respective air bladders.
- $1,240 Venturi pumps (8 at $155 each) to create reverse air flow out of the actuators as needed.
- $7,500 Universal Laser Cutting Machine to precisely cut the fabrics used in reinforcing the actuators as well as other precision cutting tasks for the radiation-transparent and non-magnetic PVC foam encasement.

1.1.4 Supplies

$11,176 for Y1 and Y2, for silicone materials, fabric, pressure transmitters, load cell and displacement sensors, hand-held corona device and other general-purpose lab materials.

1.1.5 Travel

$5,000 per year for travel to scientific conferences for all project members.

1.1.6 Publications

$4,000 per year is requested for open access publication in journals as results may be of potential interest to the general public.

1.2 Independent Phase, 3 Years

1.2.1 Personnel: Olalekan Ogunmolu, PhD, *Principal Investigator, 12-month calendar year effort*

The total estimated salary for Dr. Ogunmolu in the three years of independent phase of the award is $330,000. Fringe benefits have been estimated at 30% which is based on the University average for Fringe benefits for current junior faculties at many Tier-1 research institutes, but with an understanding that it may change based on the requirement that the institution where the independent position is secured will be responsible for a portion of the salary.

1.2.2 Other Expenses

Health insurance is requested based on the University of Pennsylvania published rates for FY21.

1.2.3 Equipment

$6,500 In the independent years, I will not have access to Dr. Wiersmas FDM 3D printer. Therefore, an FDM 3D Printer is requested to 3D print molds, and robot components.

1.2.4 Travel

$5,500 per year is requested for travel to scientific conferences, adjusted for inflation from the K99 years.

1.2.5 Publications

$4,000 per year is requested for open access publication in journals as results may be of potential interest to the general public.

Project Summary/Abstract

Targeting dose to submillimeter or subdegree accuracy to tumors in a patient's target volume is crucial for successful tumor control. Currently, computed tomography (CT) images are employed in segmenting critical structures from organs-at-risk (OARs) in radiation therapy (RT). CT images however exhibit low delineation contrast for the soft tissues of brain and head-and-neck (H&N) lesions. Magnetic resonance imaging (MRI) techniques can be an effective means for diagnosing tumors owing to its clear-cut internal tissues imaging capabilities. Recently, researchers have started exploring a combination of MRI with linear accelerator RT to assure a better tumor control. The artifacts that arise from inadvertent patient head motion within the tubular structure of the MR are however a downside to realizing a better soft tissues' delineatio; this hampers effective tumor control. The excursions of head motion outside a given confidence band is a problem that hinders the effectiveness of other radiation oncology beam targeting techniques such as stereotactic radiosurgery or highly conformal H&N RT.

Today in clinics, the state-of-the-art is to immobilize the patient's head with rigid Brown-Robert-Wells SRS head frames or thermoplastic face masks. Patients find these devices to be inconvenient, and highly invasive nature. Matter-of-factly, it causes poor patient compliance with prescribed radiation dose or poor clinical efficiencies. For patients with extreme cranial anatomy or prior surgical bone flaps, frame placement is impossible. Research aimed at eliminating the frame through thermoplastic face masks have resulted in less accuracy as mask flex can lead to systematic drift of up to 2-3 mm away from the intended target – owing to rotation about the fulcrum at the back of the skull. More so, mask-based immobilization accuracy is highly dependent on mask manufacturing quality, skill of the person applying the mask, shrinkage of the mask during treatment, and physical changes of the patients head due to swelling or weight. In my previous investigations, I have shown the effectiveness of soft robots at head motion correction up to submillimeter accuracy. Even so, Wiersma et al have demonstrated a frameless maskless robotic SRS system that can stabilize head motion to under 0.5mm/0.5deg for 99% of treatment time. In this sentiment, we hypothesize that a soft manipulator, actuated by compressed air, and adaptable to the confined space within the MR machine and under the MR coils can further help eliminate these motion artifacts that lower MR imaging quality and treatment efficacy in SRS scenarios. We will develop a motion-planning algorithm and construct a full-scale soft robot for a real-time patient head motion correction that is adaptable to MR machines and emerging MRI-linear accelerator treatment procedures. When this has been tested on phantoms human volunteers, we will validate its suitability on human trials at the University of Pennsylvania's radiation oncology clinic.

Project Narrative

Accurate dose targeting to malignant cancers in radiation oncology requires clearly delineated and richly contrasted soft tissues within the human body so that the treatment examiner can clearly tell critical structures apart from organs-at-risk. Currently, CT images are used in this segmentation task which lack these delineation capability. This project will leverage the high-contrast that magnetic resonance scans provide with the non-magnetic and radio-transparent compliance that soft robots provide cranial position manipulation so as to assure better clinical outcomes for head and neck (H&N) as well as brain cancer treatments in maskless stereotactic radiosurgery. This will further accelerate the current maskless and frameless brain and H&N cancer research by making it more available to a wider population of patients.

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2 Facilities and Equipment

Specific Aims

Integrating magnetic resonance imaging (MRI) functionality with radiation therapy (RT) linear accelerator (LINAC) can better render the visualization of the soft tissues of lesions and surrounding healthy organs-at-risks (OARs) during cancer RT treatment planning and procedures. This is because MR scans, in contrast to the prevalent computed tomography (CT) scans used in clinics today, provide a richly contrasted image of internal body tissues. More importantly, MRI-LINAC integration can be done in an unrivaled, online, and real-time fashion to aid a more precise radiation dose delivery in RT [1]. However, the quality of MR scans are limited by head motion artifacts. Given the consistency of head motion requirement for proper beam targeting in stereotactic radiosurgey (SRS) and highly conformal head-and-neck (H&N) RT, rigid head frames or thermoplastic face masks are currently clinically used as static head immobilizers. However, frames are uncomfortable and highly invasive – causing poor patient compliance and clinical inefficacy; and masks reduce dose targeting accuracy – since mask flex can lead to drifts of up to 6 mm from an intended target. Robot mechanisms for real-time head motion correction that have been investigated are made out of linear actuators and rigid metallic components which are incompatible with MR [2–4]. During my PhD, I used soft manipulators for head motion correction in RT treatment planning in lower task space dimensions. Here, we propose a novel non-magnetic and radiation-transparent soft robot for automating the online, real-time patient head motion correction in emerging MRI-linear accelerator (LINAC) RT treatment procedures. Our team, comprised of material mechanics, medical physics, control systems and soft matter experts, will address these issues via the following specific aims:

K99 Aim I: To Develop a Distributively-Innervated, Non-magnetic, and Radiation-Transparent Soft Actuator.

My preliminary soft manipulator designs have been used to control H&N motion in RT for up to 3 DoFs. This aim will scale my previous designs to a fully parallel soft robot capable of providing head manipulation along 6 DoFs and will be integrable with pre-existing LINACs. The actuators will be fiber-reinforced to constrain deformation along specific Eulerian directions in order to simplify control. Made entirely out of radio-transparent and non-metallic parts, this Gen 2.0 design will be adaptable under MR coils and the large tubular MR magnets and hence suitable for patient head motion compensation in emerging MRI-LINAC treatment procedures. A hierarchical sensing and control scheme is proposed: the soft actuators will deform in a manner similar to the fast activation ($\leq$2secs) of, for example, the papillae of the octopus, and will have rich surface innervation (e.g. similar to the cuttlefish skin) to aid rich system state perception; this will enable accurate feedback control of the pressurization within the actuator's air chambers. *We expect that this bleeding-edge application will demonstrate for the first time that soft actuators can excel at precise deformation schemes that are safe and compliant for real-world medical applications.*

K99 Aim II: To Develop a Multi-Modal and Robustly Stable Optimal Motion-Planner.

Our preliminary results show the need for a head manipulation motion planner that is safety-aware for executing optimal collision-free paths between transition modes such that manipulating the patient's head does not expose normal brain tissues to high radiation doses. This aim will find a robustly stable and optimal head motion trajectory for moving the head from a start location $\xi_i \in SE(3)$ to a goal location $\xi_f \in SE(3)$ safely. As the desired head motion is continuous with discrete underlying structures, the manipulation problem is multi-modal with a continuous admixture of modes. The current convention in robotics is to use layered planning whereby search is hastened by solving a planning problem at various abstraction levels. However, such planners often miss stability-guarantees in their optimal path formulations hence resulting in paths that are not stably robust for assuring safety in the execution of planned paths. *We will address the current gap in geometric manipulation problems under manifold constraints that leave out stability analysis by leveraging an asymptotically stable robust control Lyapunov function optimally stable motion-planning feedback controller in order to safely generate optimally-robust single modes that guide transitions that precisely move the head in the presence of medical constraints in the head-robot workspace.*

K99 Aim III: Mechanism Assembly, Phantom, and Healthy Volunteer Experiments.

A soft robot mechanism will be constructed, able to fit under the MR coils and able to (re)position the patient as needed during treatment. In addition, a 3D surface imaging sensor will measure patient's head position and feed it to the motion planner's head position feedback controller. Patient safety systems based on automated treatment beam shut off will be incorporated into the finished design. The motion-planner in K99 Aim II will be used in the real-time head motion correction in mock MRI-LINAC RT phantom and healthy human volunteer experiments. An end-to-end testing with 3D-printed head phantoms containing dosimetric gel will be used to evaluate 3D radiation dose accuracy for both single and multiple target SRS plans. A 20 volunteer study with a mock radiation beam will be conducted in a clinical environment to verify linear and angular head position control and patient safety systems.

R00 Aim: Patient Oncological Clinical Trials.

A clinical trial on 20 whole brain patients will be performed where validation of this system will be determined by a statistical endpoint. Success will be that a 6D intracranial target is $\leq$ 0.5mm and $\leq 0.5°$ for greater than 95% of the treatment time. Upon successful completion and novel use in in maskless MRI-LINAC systems, this project will demonstrate that soft robotic SRS is ready for widespread clinical deployment. With its transformational clinical potential, our soft robot head motion compensation in MRI-LINAC RT will enable the availability of novel radiation dose delivery to a larger population of patients, improve therapeutic outcomes, reduce patient invasiveness, improve clinical efficiencies by reducing current setup times from hours to minutes, and will be compatible with thousands of pre-existing LINACs.

Future Plans: **I plan to expand this project into my own independent research laboratory where I will study to design and control soft robots for broad biomedical engineering applications in human-robot interfaces.**

3 Research Strategy

3.1 Significance

Integrating magnetic resonance imaging (MRI) functionality with radiation therapy (RT) linear accelerator (LINAC) can better render the visualization of the soft tissues of lesions and surrounding healthy organs-at-risks (OARs) during cancer RT treatment planning and procedures. This is because MR scans, in contrast to the prevalent computed tomography (CT) scans used in clinics today, provide a richly contrasted image of internal body tissues. More importantly, MRI-LINAC integration can be done in an unrivaled, online, and real-time fashion to aid a more precise radiation dose delivery in RT [1]. There are now MRI-LINAC systems such as the ones developed by Raaymakers et al [1, 5], further commercialized by Elekta AB (Sweden) [1]; it uses a 1.5 T diagnostic image quality MRI system from Phillips Ingenia in conjunction with a linear accelerator. The MRIdian system is another one of such technologies, essentially an MRI-based image-guided RT [6] that was developed by Viewray (USA). There is the Aurora RT system from MagnetTx (Canada) [7], or the non-commissioned Australian MRI-Linac project [8]. While MRI-LINAC integration has been widely researched [1, 5, 9, 10], the effect of random and involuntary patient motion causes motion artifacts which lowers the quality of MR imaging scans for use in brain and head and neck (H&N) RT. These artifacts in image collection lower the accuracy of online and real-time precise radiation dose delivery, which in turn affects clinical efficacy.

Therefore, it is paramount to keep the patient accurately positioned on the treatment table, especially in applications aimed at more precise irradiation using the newly emerging MRI-LINAC machines. The importance of accurate patient positioning is further underscored by accumulating evidence that patient displacement and collimator and gantry angle misalignment during RT showed high sensitivity to small perturbations: a 3-mm error in anterior-posterior direction caused 38% decrease in minimum target dose or 41% increase in the maximum spinal cord dose [11]. Thus, to automatically align patient motion during RT, state-of-the-art clinical approaches use either a frame or a mask to stabilize patient motion on the treatment couch.

3.1.1 Known roles of frames in positioning compensation

In frame-based approaches, a metal ring is attached to the patient's skull using screws, and then bolted to the treatment table, Fig. 1a. Treatment discomfort and severe pain often results from long hours of minimally invasive surgery where the skull is fixed with pins for head immobilization during stereo-tactic radiosurgery (SRS). The invasiveness and discomfort associated with the frame are a principal cause of poor patient compliance and poor clinical efficacy. For some patients, frame placement is not possible due to extreme cranial anatomy or prior surgical bone flaps. In cases where multiple radiation therapy (RT) deliveries are needed, patients cannot be subjected to daily attachment and removal of the frame.

3.1.2 Known roles of masks in positioning compensation

These limitations of frames have spurred clinics to start using thermoplastic face masks. Here, a porous mask is deformed to fit the geometry of the patient's head and neck region and then fastened to the treatment table. As the mask is flexible, during the course of treatment, it loses its firmness around the patient so that accuracy of dose targeting is inevitable. The flexibility of mask has been identified to cause a drift of up to 2-6mm. This is unacceptable given the AAPM TG-42 positioning accuracy guidelines that specify < 2 mm accuracy [14]. Changes in the mask's physical texture from repeated application and shrinking, Fig. 1b, can also lower treatment accuracy. These inconsistencies are not suitable for deep tumors located nearby critical structures such as the brain stem or for newer treatment modalities such as single isocenter multiple-target SRS, which are highly sensitive to rotational head motions. Even so, conventional LINACs used at most cancer centers are insufficient for the high geometric accuracy and precision required of SRS for isocenter localization [15].

3.1.3 Known roles of rigid robots in positioning compensation

To overcome these issues, explorative robotic positioning research studies have demonstrated the feasibility of maintaining stable patient cranial motion consistent with treatment plans. For example, the Wiersma Lab's Stewart-Gough (SG) platform [2, 16, 17], illustrated

(a) The BRW SRS Frame [12] *(b)* Frames with MRI Coils *(c)* Wiersma SG-Robot [13] *(d)* Ostyn's Stewart platform [4]

Figure 1: Existing frame and mask (a-b), and frameless and maskless robotic systems (c-d).

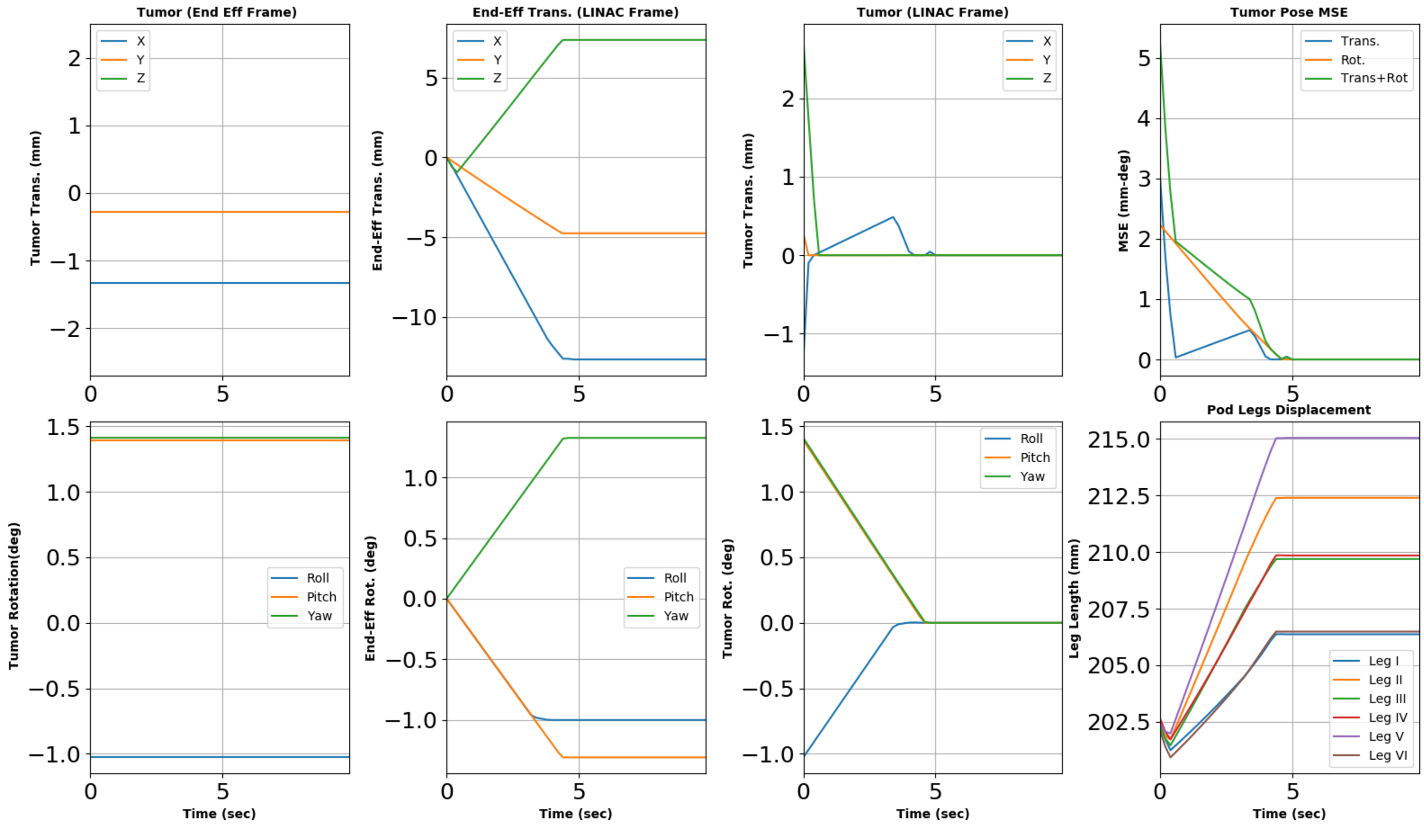


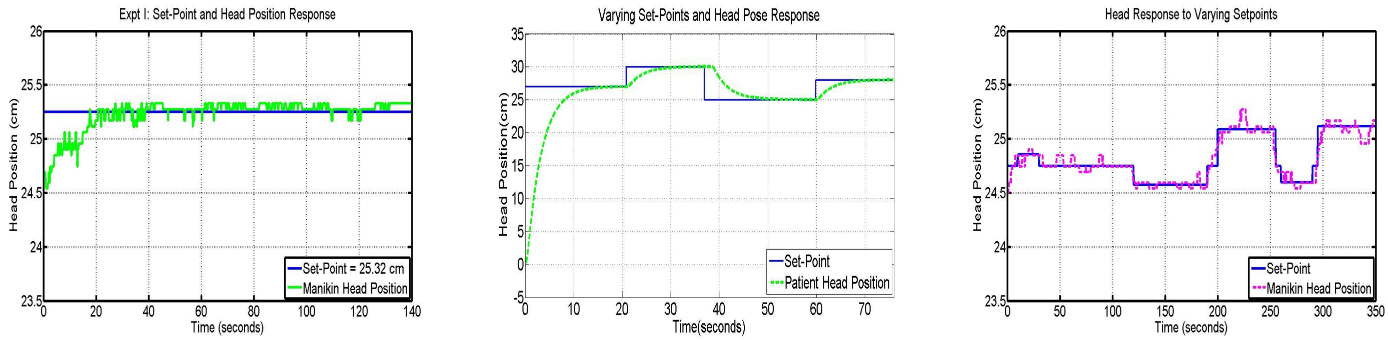
Figure 2: Isocenter Head Stabilization Results Using the Wiersma Rigid Stewart-Gough Platform. Reprinted with permission from [17].

in Fig. 1(c), achieves ≤ 0.5mm and $\leq 0.5°$ positioning accuracy 90% of the time. It is constructed as a 6-6 SG platform out of linear actuators, electric motors and rigid metallic components. While effective at head position compensation in SRS treatment procedures, it is not adaptable for new MRI-integration with LINAC RTs that offer better real-time soft tissues delineation for a precise radiation dose delivery. The Ostyn et al research group sought to alleviate this rigid build structure by 3D printing the mechanical components of the Stewart-Gough platform [4]. It is worth noting, however, that this platform uses stepper motors as well (see Fig. 1(d)) to actuate the legs of the robot. This by nature leads to radiation attenuation. With the potential to aid better clinical accuracy in SRS-based systems when commissioned, these systems are not suitable for the emerging MRI-LINAC machines. This is because they utilize rigid metallic components, electric motors and linear actuators which are not suitable for the large tubular magnets of the MR machine: they interfere with the magnetic fields of the MR machine and have been known to lead to patient fatality or significantly damage the MR machine when clinicians have been careless about bringing metallic materials into the treatment room [18] .

3.1.4 Known roles of soft robots in RT

Published work from the Wiersma lab shows that a rigid parallel robot can provide the online, real-time patient motion compensation in mock SRS and RT treatments (see Fig. 2). Here, using an LBFGS-based trajectory optimization formulation for patient head motion compensation, the algorithm was able to maintain a ≤ 0.5mm and $\leq 0.5°$ clinical tolerance objective for 100% of the treatment time [17]. But observe that not all constraints are adhered to: for example, observe the overshoot along Z for the tumor in the LINAC frame and the wriggly trajectories along the rotational axis of the tumor before it reaches steady state. *It is my hypothesis that a motion-planner that continually refines found paths, in the presence of manifold constraints, in the robot-head workspace can alleviate this*. Furthermore, while this robot does work well for SRS treatment procedures, it does not translate to integrating MRI functionality with LINACs owing to its structural mechanical characteristics.

My preliminary work on soft manipulators for patient head motion compensation in RT shows that novel soft robot manipulators can compensate head motion within the submillimeter and subdegree accuracy of the AAPM-TG42 stipulation for up to 3 DoFs [19–22]. In a cascaded PID-PI controller loop, I initially showed head motion correction for head setpoint- and trajectory-following to be accurate to within ≤ 1.5mm for a task of lowering or raising the head along 1 DoF on a treatment table [19]. These results are duplicated in Fig. 3. Furthermore, Fig. 4 illustrates the testbed used in generating the 3-DoF control results of Fig. 5. Here, the setup consists of a phantom with a neck simulator that models the ball joint in the human torso. A vision-based 3D sensor acquires the face's point cloud in real-time, which is then processed for features-extraction and the 6D coordinates of the head (here using the tip of the nose) are sent to a microcontroller (National Instruments®myRIO); the myRIO then regulates the flow of compressed air into a set of proportional



(a) Head response to fixed setpoint. *(b)* Head trajectory follower simulation *(c)* Head trajectory follower experiment

Figure 3: 1-DoF Online, Real-Time Head Motion Correction. Reprinted from [19].

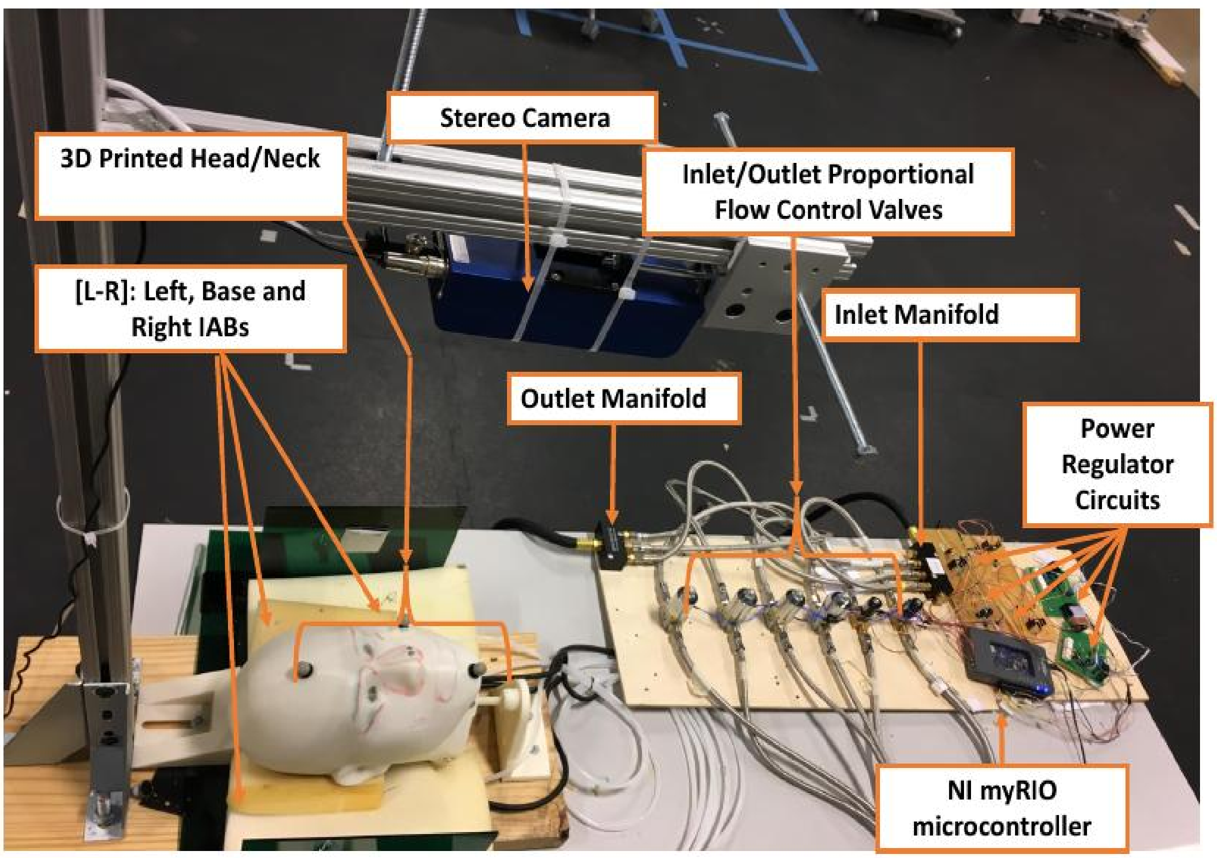
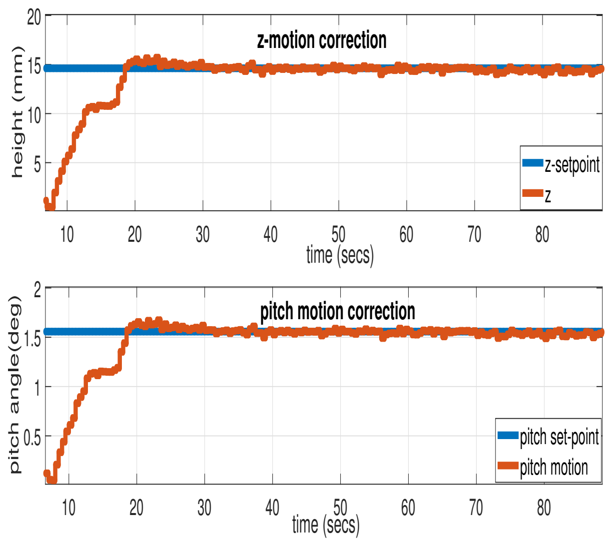


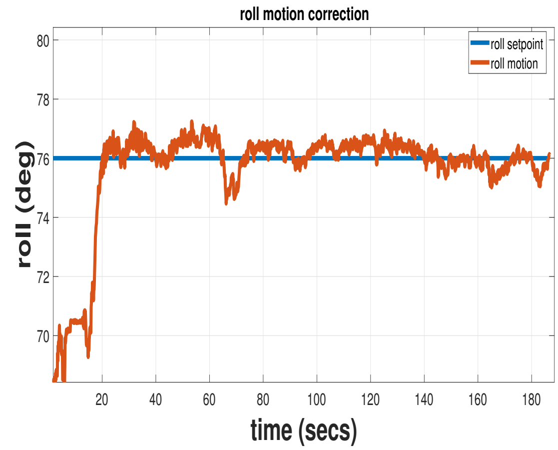
Figure 4: Three DoF Testbed. Reprinted from [20].

solenoid valves. The amount of air within the set of inflatable air bladders (IABs), in turn raise, lower, or tilt the head on the mock treatment table. The dynamics of the head interaction with the IABs and air pressure supply were carried with a lumped prediction error model [23]. This model was then used in a controller that leveraged indirect model reference adaptive control with optimal state regulation in order to ensure the head follows set trajectory through steady-state [20]. Some of these results are reprinted in Fig. 3 and Fig. 5 respectively.

Now, in a new class of soft actuator designs, and contrary to stochastic system identification techniques I used in my previous models [19,20,22], we can now specifically regulate volume fractions within the IABs as well as accurately control their spatial deformations based on specific nonlinear elastic deformation relationships [24]. Being continuum, compliant and configurable (C3) for manipulation tasks, we recently demonstrated in control experiments that they are as well capable of providing patient head motion compensation [13]. Contrary to remote-controlled airbags that have been used in upper mandible and head manipulation [25], our actuators deform based on their material moduli, compressed air pressurization and incompressibility constraints when given a reference trajectory. To our knowl-

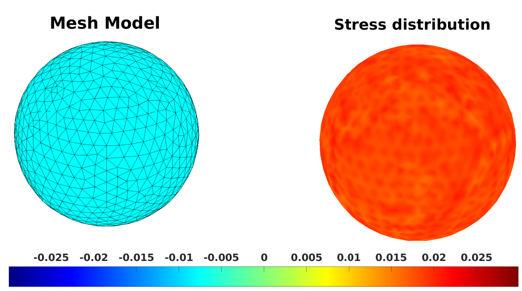


(a) Z and pitch motion correction.

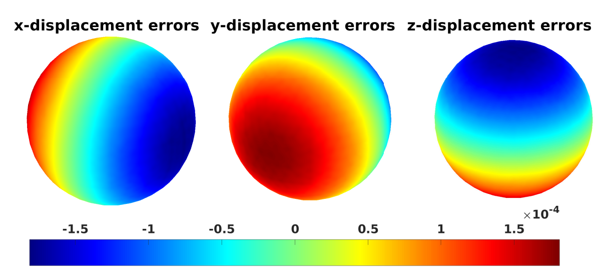


(b) Roll motion correction.

Figure 5: 3-DoF Online, Real-Time Head Motion Correction. Reprinted from [20].



(a) **Left**: Mesh model. **Right**: Stress distribution post-defomation.



(b) Displacement errors along x, y, z coordinates.

Inputs					Outputs		
C_1	C_2	$R_i(mm)$	$r_i(mm)$	$R_\circ(mm)$	$r_\circ(mm)$	$P(psi)$	ΔV
$1.1e4$	$2.2e4$	2.7	3	3	3.3	.76	≈ 0

Figure 6: Volumetric Deformation of a Soft Actuator (Expansion). Reprinted from [24].

edge, ours are the first to explore C3 materials as actuation systems for cranial manipulation in robotic radiotherapy. Deforming based on prescribed internal pressurization, their surface displacement errors are accurate to the order of $< 1.5 \times 10^{-}4$mm [24]. These results are reiterated in Fig. 6 where a spherically-textured soft actuator was prescribed to deform from an initial internal radius, $R_i = 2.7$mm from the reference configuration to $r_i = 3.3$mm in the current configuration. Based on my derived constitutive relation between the applied pressure and the radius of the actuator, a pressure of 0.76 psi was found to be suitable to realize this deformation. The charts of Fig. 6 illustrates the response of the actuator based on a prescribed pressure, where C_1 and C_2 are appropriate material moduli. With the standard local volume preservation principle, we notice a displacement error of 1.5×10^{-4} along the rectangular Cartesian coordinates and a zero volumetric change$i.e.$ $\Delta V \approxeq= 0$. This shows that with *highly accurate pressure sensors*, and equipped with properly calibrated proportional solenoid valves, we can regulate the air within a soft actuator's chamber so that specific and highly precise deformation behaviors are realizable for consumer soft actuators.

3.1.5 Hypothesis

My **leading hypothesis** is to use MRI/LINAC-compatible soft robot system that can provide 6-DoF head motion correction in precision RT procedures to serve as a viable alternative to current mask-based as well as frameless and maskless robot-based cranial manipulation systems. In this sentiment, **I hypothesize that time-resolved MRI-LINAC techniques, which provide superior soft tissue scans, in conjunction with non-magnetic and radiation transparent soft robots can provide superior brain or H&N radiation dose targets**

for precise MRI-LINAC RT treatment procedures. Existing frame-based immobilization devices, Fig. 1a&b, and frameless and maskless rigid robotic motion correction mechanisms, Fig. 1c&d, are not suitable for this because of their electro-mechanical parts that introduce serious safety concerns. Furthermore, **I hypothesize that an asymptotically stable in the large and optimal motion-planner can find collision-free paths that satisfy head motion constraints can resolve the abnormalities inherent in current controllers used in head motion correction systems [2, 3, 16, 20]**. I will test this leading hypothesis to see if 6-DOF target motion of a patient is ≤ 0.5 mm and $\leq 0.5°$ for greater than 95% of the treatment time using MRI imaging for soft robot-based motion compensation.

Along with other experiments where I verified that vision-based control of soft robots can geometrically correct patient motion precisely fast-enough in real-time up to three DOFs [19–22], and existing hybrid MRI-compatible RT systems [5, 9, 10], we will test these hypotheses that soft robots can provide position accuracy that is consistent for use in standalone MRIs, MRI-LINAC RT systems or SRS-alone treatment procedures in order to (i) negate the deleterious effects of *interfractional* setup variation on patients; (ii) correct the complex *intrafractional geometric uncertainties* such as posture changes, and body deformation with minimal invasiveness; (iii) eliminate radiation attenuation associated with the metallic components of frames and rigid robotic patient motion compensation systems; and (iv) correct the flex associated with thermoplastic face masks; while *not interfering with the MR machine's magnetic field*.

3.2 Innovation.

Our study is innovative in the following respects:

- my work was the first to demonstrate the feasibility of vision-based 3 DOF control of soft manipulators for cranial motion management in RT [19–22]; we are extending this to 6-DOF control with my novel advanced mechanism;
- this mechanism is made entirely of no metal (hence not susceptible to magnetic fields) and is radiation-transparent so that it is compatible with both MRI-LINACs;
- this mechanism can be adapted to confined spaces under MRI coils (see Fig. 1b) given its compactness, and light weight.
- it possesses little invasiveness to the patient, and
- exhibits a quick-connect, quick-disconnect modularity on a couch – important for patients with varying cranial anatomy – thus easing the logistical setup workload of current immobilization and maskless robotic systems.

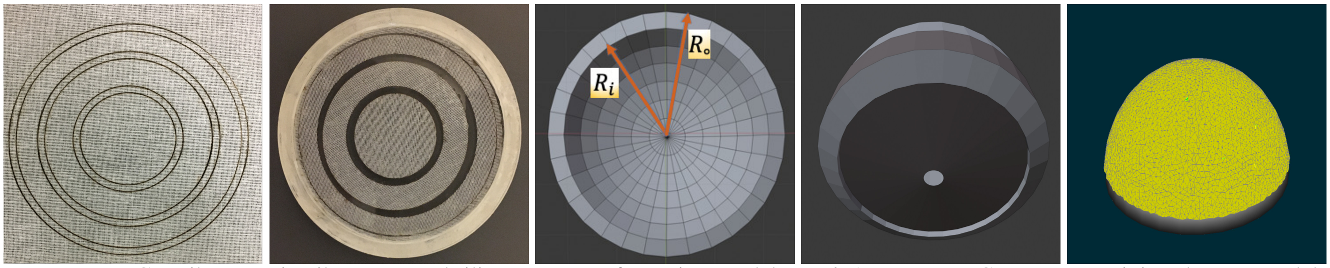
To our knowledge, **no currently-available technology exists today that can perform real-time head position stabilization *without dose attenuation* in an online, real-time fashion whilst guaranteeing patient safety similar to our proposed MRI-LINAC non-magnetic and radio-transparent soft robot RT positioning system**. As photon-based cancer treatment accounts for $> 50\%$ of all cancer treatments [26], these exploratory experiments are relevant to public health and have transformational clinical potential because they may provide (i) proof-of-concept evidence that soft robots are compatible with standalone MRI imaging modalities; (ii) evidence of precise and automatic motion management with non-magnetic and radiation-transparent soft robots in emerging hybrid MRI-accelerator RT; (iii) an emergence of a better brain and H&N cancer management technology that can be adapted to confined spaces under MRI coils (see Fig. 1b). Upon successful completion, this soft robot will be used for active head motion stabilization within an MR machine. It will be adaptable for standalone MRIs, emerging MRI-LINAC technologies, and brain as well as H&N RTs. It will provide accurate RT beam targeting as well as preventing patient motion MRI imaging artifacts. This technology will improve therapeutic outcomes, and eliminate patient invasiveness.

3.3 Approach.

3.3.1 K_{99} Aim I: To Develop a Distributively-Innervated, Non-magnetic, and Radiation-Transparent Soft Actuator.

Rationale: For though the design of § 3.1.4 is relevant to head motion control on an RT treatment table, it is not a complete motion correction system owing to its underactuated mechanism: it is only able to correct motion for up to three DoFs. Motion of the head occurs along six DoFs and they are not independent. Therefore, to realize a full patient motion compensation, more actuators are needed in the mechanism. To this end, and iterating further on my previous designs [20–22], I now propose a new class of continuum, compliant and configurable (C3) light, and agile soft actuators [24, 27, 28] which are the composition of a non-magnetic and radiation-transparent soft robot for use in MRI-LINACs to further aid dose delivery precision. The component soft actuators are planar and circular in their reference configuration. Upon compressed air actuation, they deform along the radial direction (see computer model in Fig. 7) based on the physical constraints baked into the elastomer-fabric matrix. This actuation design is inspired by the behavior of the skin papillae of certain Cephalopods (octopus, cuttlefish, bivalves and mollusks) which can transform their physical texture from 2D to 3D in less than 2 seconds [29, 30]. The actuators exhibit a radially symmetric deformation and are constrained along their circumferential axis under pneumatic actuation based on their novel design. There exists no electrical wirings or embedded electronics to assure that the actuators reach a desired configuration.

Hypothesis: Based on previous success of air actuated elastomeric chambers for manipulating patient head motion correction in real-time, I hypothesize that a fully-compliant and parallel soft robot can effectively correct patient head motion (given a robustly stable and



(a) Laser-Cut Fiber *(b)* Fiber+Uncured silicone *(c)* Deformation Model *(d)* Actuator+PVC Base *(e)* Finite Element Model

Figure 7: Soft actuator fabrication procedure.

optimal controller) such that the motion artifacts that are prone in MR imaging can be eliminated. This will assure an improved RT treatment outcomes in modern MRI-LINAC RTs.

Procedure.

A. Soft Actuator Design: The soft actuator fabrication methodology is illustrated in Fig. 7. A thin-layered fabric is laser cut into circular patterns (Fig. 7a), the cut meshes are removed and laid onto uncured silicone (Fig. 7b) which has been poured into mold. We further add a silicone topcoat layer to the fabric before we allow it to cure. Upon low pneumatic pressurization, the cured rubber deforms, obeying a Circumferentially-COnstrained And Radially Stretched fiber-Elastomer (CCOARSE) property [31] (Fig. 7c). This unique deformation pattern is similar to the way a balloon would stretch along its axial direction if a rope were tied around its circumference. The soft robot, after cure, is laid onto an impact-resistant, low-temperature rigid PVC insulation foam sheet, encased in a carbon fiber material. This aids radiation transparency (Fig. 7d). The finite elastic deformation mesh model of the soft robot for simulation purposes is shown in (Fig. 7e). This proposed fabrication method allows us to rapidly iterate different designs using compressed low air pressure (1-15 psi) that is (i) cheaply available, (ii) environmentally-friendly, (iii) avoids electrical wirings, (iv) is lightweight, and (v) inviscid which will make the soft robot adaptable for MRI-LINAC systems – creating a clean and safe human-robot workspace. As the air inflow into the air chambers of the elastomers need to be carefully regulated, we will build current source electronic regulator circuits that proportionally vary the amount of airflow though connecting hoses that lead into the proportional solenoid valves used in earlier experiments [20].

B. Pneumatic System Design: We now describe the integration of the soft actuator design proposed above with the rest of the pneumatic actuation system. This system is illustrated in Fig. 8. A self-contained compressed air canister supplies air at a fixed pressure (e.g. 15 psi) through a firm polyurethane air tubing into a 4-20mA output-M12 pressure transducer plug connection. The choice of pressure transmitter is important owing to the accuracy requirement for air volume within the chamber of the soft actuator. In our experience, the G2 series of pressure transducers from Ashcroft®are an excellent choice for such application as this: it offers a $\pm 1.00\%$ total error band accuracy; being highly configurable, it offers a pressure range that meets our actuation needs and it can be easily integrated into our overall mechanism. The outlet of this pressure transmitter conveys the airflow into a proportional solenoid valve. We use proportioning valves to control the amount of airflow into the actuator's air chamber because of the air flow precision requirement needed to correctly manipulate the head. The outlet of this solenoid valve then leads to the inlet air connector of the soft actuator. The electronic regulating circuit shown in Fig. 8 is a standard current source circuit that varies the air flow rate within the proportional valve by adjusting the current flowing through its shunt resistor. In addition, a venturi pump removes air at a proportional pressure compared to the inlet supply pressure. This pressure differential helps maintain head along a setpoint or follow a varying trajectory.

C. Preliminary Actuation Experiments: We have initial experiments that reproduces deformation behavior similar to the spike observed in the skin papillae of the Octopus. This is described in what follows. We cast silicone from Smooth-On Inc's dragon skin (475 psi tensile strength and 10A shore hardness), whose material properties exhibit enough softness for patient comfort and enough firmness that withstands extremely nonlinear deformation from the wrench produced by the typical human head (55-65 kg [32–34]. The ingrained fabric membrane within the elastomer imposes the CCOARSE property, constraining the circumferential expansion of the rubber and exerting a radially symmetric stretch as shown in the bottom row of Fig. 9. This considerably simplifies the dynamics model that governs the deformation [28]. Two different designs are shown in the top and bottom rows of Fig. 9. The rubber material is screwed onto a bottom PVC foam sheet using a laser-cut acrylic planar ring. We use **nylon** Phillips screws. The behavior at different levels of pressurization are indicated in each column of the figure. The top row shows the cured silicone without fabric while the bottom row shows the silicone with the entrenched fiber matrix within the elastomer. As can be seen, the material in the top row exhibits a circumferential bulge as well as radial bulge while the ones in the bottom row only extend along the axial direction. As can be seen in the bottom row, we can generate a full *Gaussian deformation* and return to the reference planar configuration in 2 seconds (see more images and videos in scriptedonachip.com/soro) similar to the spikes produced by the skin papillae of the Octopus. These quick Gaussian spikes will be useful for rapid head motion correction in MRI-LINACs. 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.

D. Flexible Piezoresistive Distributed Sensor Integration: In a recent formulation [24], we mapped the relationship between the

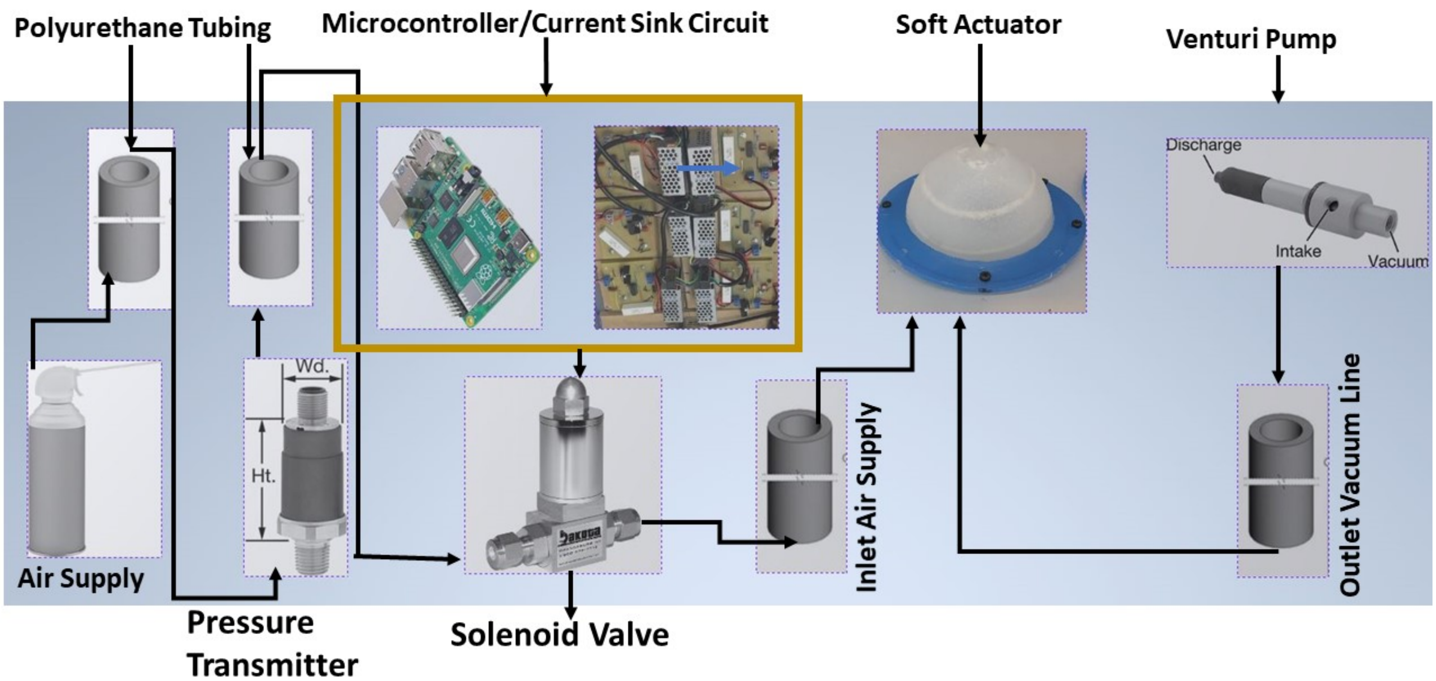


Figure 8: Pneumatic System showing proportional solenoid valve, electronic pressure regulators and raspberry pi microcontroller.

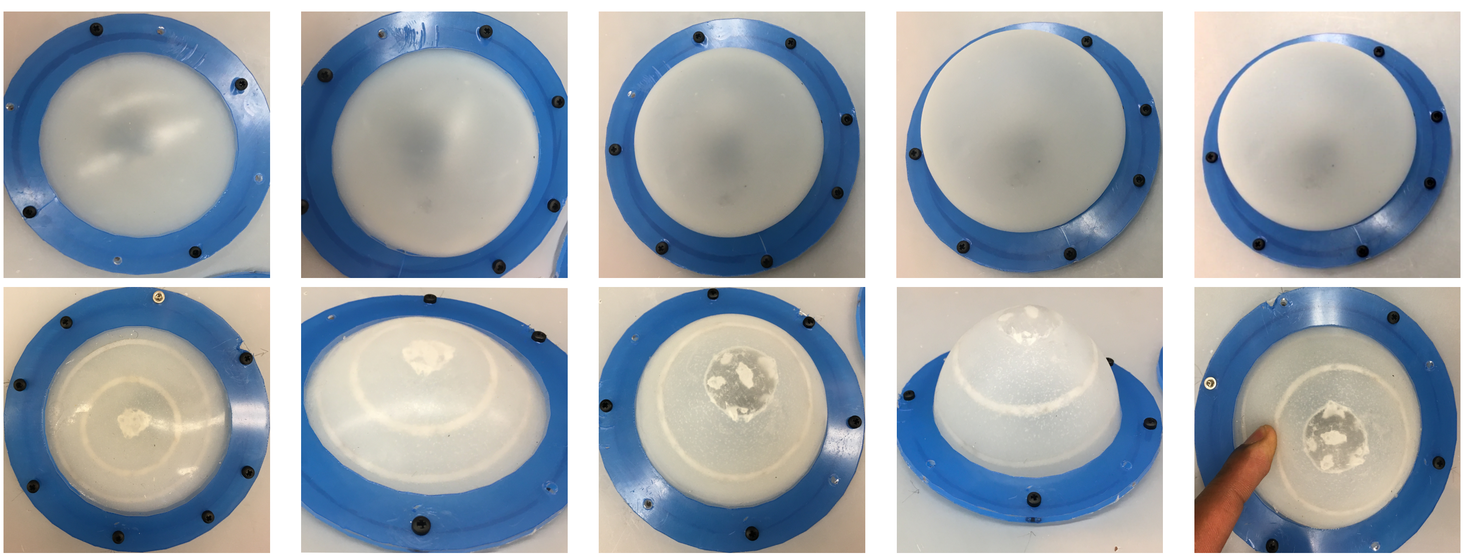


Figure 9: Deformation Levels of elastomer (top) and Elastomeric-Fiber Matrix (bottom) under Low Air Pressurization (3-15psi).

applied pressure to the deformed radius of a soft actuator using the standard Mooney-Rivlin formulation [35, 36]. Suppose that C_1 and C_2 are appropriate material moduli for the soft actuator, then the applied pressure in the internal walls of the actuator is given by the relation

$$P(r) = \int_{r_i}^{r_\circ} \left[2C_1 \left(\frac{r}{R^2} - \frac{R^4}{r^5} \right) + 2C_2 \left(\frac{r^3}{R^4} - \frac{R^2}{r^3} \right) \right] dr \tag{1}$$

where r_i and $r_\circ$ are respectively the internal and external radius of the actuator walls in the current configuration, and they have corresponding forms R_i and $R_\circ$ in the reference configuration. Taking cues from the precise control schemes of rigid robot manipulators made possible by presence of joint encoders and harmonic drives that enable precise control of the joint angles between robot links, a means of sensing the "measure of deformation" based on the amount of pressure in the actuator's air chamber is necessary for a successful control.

There have been various measures proposed in literature over the past few years about sensing volumetric deformation of a soft actuator. For example, embedded optically-laced fiber sensors based on the principle of frustrated total internal reflection, and distributed throughout a 3D printed elastomer, were used to generate a cointegrated body, sensing, and communication network for a soft robot's state sensing [37]. They have also found applications in innervated soft finger prosthetic hand designs [38], where a very lossy optical waveguide was used in an open-loop control setting to detect shape and texture. While in softness grasp dexterity, they appear promising, they are not yet suitable for human-level texture-based sensitivity (nanometers) despite their complex design. Stretchable sensors with rheological properties have been erstwhile embedded within an elastomer using 3D printing techniques [39]; and though they have been shown to be mechanically receptive, and scalable up to e.g. $\sim$400% strain, their electrical resistance gives at strains $> 400\%$ owing to the percolation of the networked components [39]. Pneumatic actuator networks patterned within an elastomeric robot body via a multi-material, embedded 3D printing technique have been tried [40]. Dielectric elastomers (DE) making use of the static charge properties of passive electronic components have been shown capable of measuring strain by up to 1692% under the Maxwell pressure law [41]. This DE actuators generally rely on electrostatic voltage discharge to sense deformation [42].

Owing to our precise manipulation requirement, a richly innervated means of sensing actuator deformation at high strains (owing to large reactive head forces) is necessary for effective closed-loop feedback control of head motion. Borrowing cues from the observational and short/long-term learning skills arising from the afferent neural networks on the exteroceptive skins of Cephalopods [30, Ch. 2], we will integrate volumetric tactile mechano-receptors on the soft actuators' skins. As we aim to avoid rigid electro-mechanical sources hat can hamper radiation delivery within the design, we will shun DEAs. Optical waveguides would be attractive but they are expensive to integrate for volumetric sensing. Instead, I propose tactile stretchable kirigami sensors made out of polyimides (Kapton sheets) and fiberglass membranes. Meso-scale stretchable Kirigami layer-by-layer manufacture of soft robots have recently been shown to be relevant for fast and precise deployment of robots [43, 44] with high sensing accuracy . Even so, the 3D perception of the environment of these piezoresistive innervated soft robot skins can be perceived using deep learning [45]. In this sentiment, I will laser-cut electrical grade Kapton sheets, weave them in twisting formations with fiberglass materials to mimic the bending of beams that enable accurate sensing [43]. The sensors will then be neatly covalently bonded (without adhesives) to the soft actuators surface by plasma treatment [46]. The proprioception of the soft actuators will be captured by an LSTM deep-learning network such as I used in my previous works [47–49]: this will predict the configuration of each soft actuator during both prescribed and random actuation sequences, even with feedback from non-monotonic, hysteretic, soft piezoresistive sensors. This fabrication approach is attractive because (i) it allows the separation of the fabrication of the soft actuator design from the piezo-resistive sensors; (ii) we can separately characterize the deformation sensing properties of the piezoresistive fiberglass-polyimide sensors for QA purposes before respective integration onto the component actuators; and (iii) it offers a modular and cheap fabrication design methodology that eases troubleshooting during the construction phase.

E. Expected results: Based on the series of experiments proposed in this section, I expect to see individual soft actuators obeying the prescribed pressure law given in (1) so that the deformation radius of the actuators exactly follows an applied pressure similar to the presented simulation results of Fig. 6, further elaborated in [24]. In addition, as I am skilled and well-versed in inference using deep-learning methods (see representative publications [47, 48, 50, 51]), I expect that the stretchable Kirigami sensor layers embedded within the elastomeric actuator membranes will produce rich innervated data that can be processed with deep learning based methods [45] for onward control processing.

3.3.2 K_{99} Aim II: To Develop a Multi-Modal and Robustly Stable Optimal Motion-Planner.

Rationale: Current SRS-based immobilization and head motion compensation techniques are pre-programmed and heavily calibrated within their environment in order to find the optimal and safest path required in moving a patient's cranial structure from one location to another in the robot workspace [3, 13, 16, 52, 53]. Techniques used range from PID control schemes [2, 19], reduced-order observer feedback control design [22], optimal and robustly stable indirect model reference adaptive control design [20], to local trajectory optimization schemes [17]. While these schemes work manually for specific automation task, they require extensive calibration and adjustment of parameters so as to get them to work in each new environment and for every new head motion control task. For these robots to execute tasks autonomously, a motion planning system capable of generating feasible motion from high-level requirements is needed. In addition, this motion planning system must respect the constraints on a task in order achieve success, such as turning the translating the head about its cranial-caudal axis, or rotating the head about its neck fulcrum. *I will reformulate these control tasks into a manifold-constrained geometric motion planning problem, concerned with finding a feasible optimal and collision-free path for a patient's head motion.*

In order to optimally move the patient's head in an optimally safe and collision-free path that avoids the exposure of normal tissues to high radiation dose, and is not task-dependent, it is important to develop a motion-planner that (i) executes head motion in the robot's workspace by first finding a collision-free path; (ii) improves the plan into a better plan if the original plan is not efficient or does not satisfy C-space constraints; this may involve multiple iterations; (iii) considers how to move the head along a path that is stable and robust for execution in spite of modeling errors and uncertainties, while maintaining various speeds that satisfy various momentum considerations; and lastly (iv) the found plan must be included in a hierarchical planning framework so that the original plan reaches termination, in order to allow larger plans in the hierarchy to roll out as needed. This planing approach is consistent with motion planning algorithms used in robotics [54].

Hypotheses: The requirements produced by this problem and in many other safety-critical problem domains (e.g., household caretaking, IMRT, assistive robots in epileptic patients, and disaster recovery) motivate the study of safety-aware motion planners with constraints. Therefore, **I hypothesize that a layered planning algorithm will find a hierarchical multi-planning sequences of motion that biases search into *optimal mode* transitions**. This layered composition of plans will first compute collision-free paths $\mathcal{C}_{free}$ for moving the head between the start and goal poses. A higher hierarchical planning layer will then leverage encoded manipulation constraints within the robot-head interface to ensure that sensitive H&N structures are not damaged by radiation while the lower collision-free path in the hierarchy is to be executed. This layer of the planning algorithm might need to be repeatedly carried out in a fast computational loop to ensure all $\mathcal{C}$-space constraints are satisfied. Then a higher level plan takes the actions from the two previous lower level plans and generates a robustly stable controller in the sense of Lyapunov such that it can move the head along the $\mathcal{C}_{free}$ paths even in the presence of parametric errors, or uncertainty in model dynamics [20, 55, 56]. **I further hypothesize that the overall hierarchical plan be sequentially structured so that head motion transitions between *planning modes* ($i.e.$ from an initial location $\xi_i \in \boldsymbol{SE}(3)$ to a goal reqgion $\mathcal{Q}_{goal}$) are executed by leveraging online search protocols, which bias search for optimal and feasible paths to a sequence of modes that yield a smooth representation of head motion.** By these hypotheses, *I will address the current gap in geometric manipulation problems under manifold constraints that leave out stability analysis in the feedback control mode of the motion planner. I will achieve this by leveraging a Lyapunov-based stable estimator of the underlying dynamic system in safely generating optimally-robust single modes that guide transitions that precisely move the head.*

Procedure: I will formulate a stable geometrical representation of the underlying dynamical system and bias search toward optimally stable and robust short-task plans by providing an optimality-based method for choosing a control law once an robust control Lyapnov function (RCLF) [57] is known. I will develop an optimally stable and probabilistically-complete multi-modal planner that has broad applications to general multi-modal planning tasks in safety-critical problems in medical robotics.

A. Preliminaries: Let the set of all possible configurations of the head-robot system be $\mathcal{Q}$ in the C-space $\mathcal{C}$ [58]. Suppose that after a number synthesis of the proposed mechanism [59], the dimension of the robot is n. A particular configuration of the robot is defined by $\xi \in \mathcal{Q}$. We assume that the $\mathcal{C}$ is a closed and bounded metric space, and that $\mathcal{Q}$ is a measurable space $(\mathcal{Q}, \mathcal{B}_{\mathcal{Q}})$ for a $\mathcal{B}_{\mathcal{Q}}$ Borel σ-algebra on $\mathcal{C}$, generated from the metric [60]. The set of obstacles to be avoided are a closed set $\mathcal{Q}_{obs}$, which defines the free configuration space $\mathcal{Q}_{free}$, such that $\mathcal{Q}_{free} = cl(\mathcal{Q} \backslash \mathcal{Q}_{obs})$[1]. Our goal is to find a path from ξ_i to some region of interest $\mathcal{Q}_{goal} \subset \mathcal{Q}$, $i.e.$ a continuous injective map $\sigma : [0,1] \to \mathcal{Q}_{free}$ such that $\sigma(0) = \xi_i$, and $\sigma(1) \in cl(\mathcal{Q}_{goal})$. In addition, a smooth positive definite and radially unbounded function $V(\xi)$ is a control Lyapunov function (CLF) for the head-robot control affine system $\dot{\xi} = f(\xi) + g(\xi, u)$ if

$$\frac{\partial V}{\partial \xi}(\xi) f(\xi) + \frac{\partial V}{\partial \xi}(\xi) g(\xi) q(\xi) \leq -P(\xi) \; \forall \; \xi \neq 0 \tag{2}$$

where $P(\xi)$ is some positive definite function, $u \in \mathbb{R}^6$ is a control input, and $f(0,0) = 0$.

B. An asymptotically stable in the large and optimal motion-planner: Our goal is to find an optimal collision-free path, c, with respect to a CLF $V(\xi) : \mathbb{R}^n \to \mathbb{R}^d$ such that

- $V(\xi)$ is positive for all $\xi \in \mathbb{R}^d \backslash \mathcal{Q}_{goal}$; and $V(\xi)$ exhibits a unique global minimum in the target region $\mathcal{Q}_{goal}$, where $V(\mathcal{Q}_{goal}) = 0$;
- as the head moves along any of the trajectories, we must have $V(\xi^{t,n}) > V(\xi^{t+1,n})$, and $V(\xi^{T^n,n}) = 0$; $i.e.$ $V(\xi)$ decreases as time increases and $V(\cdot)$ vanishes when the actuators reach steady state after deformation;
- in addition, we require $V(\cdot)$ to satisfy the CLF requirement in (2)
- robust head motion during motion execution shall be guaranteed by devising *robust stabilizability via continuous state feedback* [57], provided that there exists an RCLF on the control-affine system.

We want to choose a control input $u = q(\xi)$ for some function $q(\xi)$ with $q(0) = 0$ so that equilibrium $\xi_e = 0$ of the closed-loop system

$$\dot{\xi} = f(\xi, q(\xi)) \tag{3}$$

is asymptotically stable in the large [61]. The first condition ensures the cost function is a valid Lyapunov function while the second option maintains the stability property in the sense of Lyapunov ($i.e.$ $\dot{V}$ being negative semi-definite for all $\xi \in \mathbb{R}^d \backslash \mathcal{Q}_{goal}$. To avoid wasting control energy and missing optimality during motion execution, as is common with the cancellation or domination of nonlinear terms in feedback linearization, the third option will leverage the *inverse optimal stabilization* in a differential game setting based on the pointwise min-norm control law of [57]. This is attractive because rather than solve a Hamilton-Jacobi-Isaacs (HJI) equation for a

[1] $cl(X)$ is the closure of a set, X.

control law that yields the path c, the pointwise min-norm control law yields a robustly stabilizable and optimal synthesis of the head motion correction problem.

C. Manifold Constraints: It is not enough for us to find a valid path c that is free of collisions. We also want the head motion to follow constraints that are functions of the robot's geometry, avoids radiation hitting critical structures, follows a path that does not increase proneness to claustrophobia [62], and lower the problem's dimensionality. Similar to [60], we define these *manifold constraints* to capture loop closure constraints, end-effector constraints etc. A forward kinematic map from the configuration of the i^{th} IAB, $\boldsymbol{\chi}_{iab_i}$, maps from respective IAB configurations to head position and orientation $i.e.$ $K_{iab_i} : \boldsymbol{\chi}_{iab_i} \to SE(3)$. The head velocity with respect to a fixed base frame in terms of IAB velocities can be written in terms of the forward kinematics Jacobian:

$$\begin{pmatrix} v_{iab_i} \\ \omega_{iab_i} \end{pmatrix} = \frac{\partial K_{iab_i}}{\partial \mathbf{r}_i} \frac{d\mathbf{r}}{dt} K_{iab_i}^{-1} = \boldsymbol{J}_i(\mathbf{r}_i)\dot{\mathbf{r}}_i \tag{4}$$

where $\mathbf{r}_i$ is the spatial position of IAB i in generalized coordinates, and $(v_{iab_i}^T, \omega_{iab_i}^T) \in \mathbb{R}^6$ represents the linear and angular velocity of the i^{th} IAB about its screw basis. In essence, $\mathbf{r}_i \in \mathbb{R}^3$ with its rows are mapped to scalars by an appropriate choice of norm[2]. The contact between the head and the IABs is mapped by the Jacobian

$$\boldsymbol{J}_{c_i}(\xi_h, \xi_{iab_i}) = \begin{bmatrix} \mathbf{I} & \hat{\boldsymbol{w}}(r_{c_i}) \\ \mathbf{0} & \mathbf{I} \end{bmatrix} J_{r_i}, \tag{5}$$

where $\boldsymbol{J}_{c_i} : \dot{\xi}_{r_i} \to \begin{bmatrix} v_{c_i}^T, & w_{c_i}^T \end{bmatrix}^T$, $r_{c_i} \in \mathbb{R}^3$ is a vector between the head reference point (e.g. the center of mass) and the contact with the i^{th} IAB, ξ_h is the position and relative orientation of the head, ξ_{iab_i} is the position and relative orientation of the i^{th} soft robot in world coordinates, $\hat{\boldsymbol{w}}(r_{c_i})$ is an anti-symmetric matrix for the vector r_{c_i}, and $\xi_r = (\xi_{r_1}, \xi_{r_2}, \cdots, \xi_{r_k}), (1 \le k \le n)$ are the positions and orientations for each of the IABs. For $\mathcal{C}^2$-smooth k-constraint functions $G_1, \ldots, G_k$ $(1 \le k \le n)$, a constraint is fulfilled when $g_i(\xi) = 0$ and we write out the composite constraint function $G : \mathbb{R}^n \to \mathbb{R}^k$ with respect to the contact Jacobians as

$$G_i^T(\xi_h, \xi_{iab_i})\xi_h = B_i^T(\xi_h, \xi_{iab_i})\boldsymbol{J}_{c_i}(\xi_h, \mathbf{r}_{r_i})\dot{\xi}_{iab_i} \tag{6}$$

for an IAB's selection matrix $B_i^T(\xi_h, \xi_{iab_i}) \in \mathbb{R}_i^m$, where m_i is the range of all the forces and moments for the chosen contact primitive (or union of contact primitives). Therefore, for k actuators in the soft robot, we have the following manipulation constraint

$$\begin{bmatrix} G_1^T \\ \vdots \\ G_k^T \end{bmatrix} \begin{pmatrix} v_h \\ w_h \end{pmatrix} = \textbf{diag} \begin{pmatrix} B_1^T \boldsymbol{J}_{c_1} \\ \vdots \\ B_k^T \boldsymbol{J}_{c_k} \end{pmatrix} \begin{pmatrix} \dot{\mathbf{r}}_{iab_1} \\ \vdots \\ \dot{\mathbf{r}}_{iab_k} \end{pmatrix}. \tag{7}$$

The details of this derivation are presented in my unpublished work [28]. We call $\mathcal{M}_{free}$ the free constraint manifold of the overall manifold, $\mathcal{M}$, which is defined as $\mathcal{M}_{free} = \mathcal{M} \cap \mathcal{Q}_{free}$.

Problem 1 (Constrained RCLF Motion Planning)**.** *Find an RCLF collision-free path $\sigma^\star : [0,1] \to \mathcal{M}_{free}$ given a path planning problem $(\mathcal{Q}_{free}, \xi_i, \mathcal{Q}_{goal})$, manipulation constraint, G, and cost function V such that $V(\sigma^\star) = \min_{\sigma \in \Sigma_{\mathcal{M}_{free}}} V(\sigma)$ if one exists.*

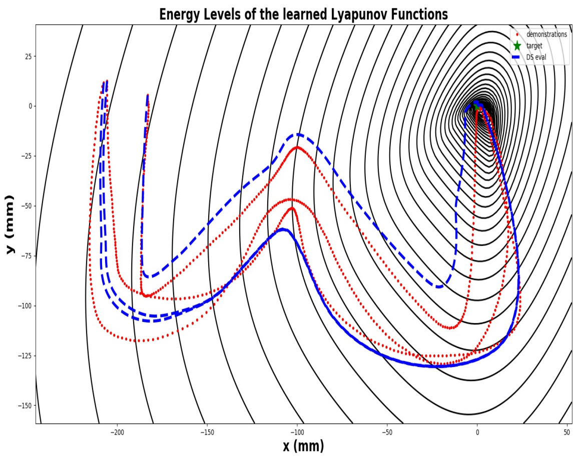
Expected results: Previously, the stabilizing command for items 1 and 2 in subsection B above was computed by solving a constrained optimization problem to choose the collision-free stabilizing command among the possible solutions. My implementation takes a greedy approach using the L-BFGS optimization algorithm with box constraints, in contrast to the quadratic nonlinear constrained optimization used by [63], to find the minimal value of the control law u at each time step such that u it is stable. Results of this implementation on toy robot nonlinear control from example demonstrations in 2D task space, implemented in python (see [64]), are reprinted in Fig. 10. When the problem identified in Prob. 1 is solved, I should expect my results to provide better trajectory tracking than the non-RCLF implementation I implemented in [64] owing to the account for all possible manifold constraints in the problem formulation.

3.3.3 K_{99} Aim III: Mechanism Assembly. Phantom and Healthy Volunteer Experiments.

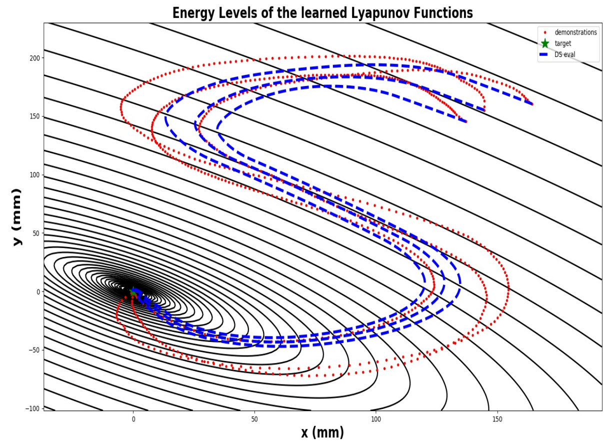
Rationale.

Case for a parallel soft manipulator: Open-loop kinematic chains have a low transportable load and poor accuracy since the weight of the segments that follow each link and the load of the structure contributes to the large flexure of torques; their links magnify errors from shoulder out to the end-effector, consequently hampering their use for sophisticated control strategies that may minimize or eliminate load-dependent error. Thus, most serially-joined manipulators are stiffened during the manufacturing process – thus, inherently exhibiting a high load-to-weight ratio and a complicated actuation system. Moreover, their passive bending stiffness overwhelms the degree of deformation. Parallel configurations, in spite of their higher number of actuated joints, distribute the weight of the load around the links of the robot, improve manipulation accuracy, have 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. Given the non-cummulativeness of actuator errors in parallel configurations, greater precision is possible with minimal control-complication [65].

[2] I used the $l2$-norm im my implementation.

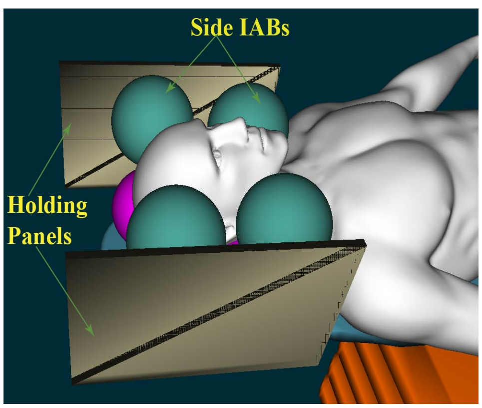


(a) Reproducing a nonlinear W-shape motion

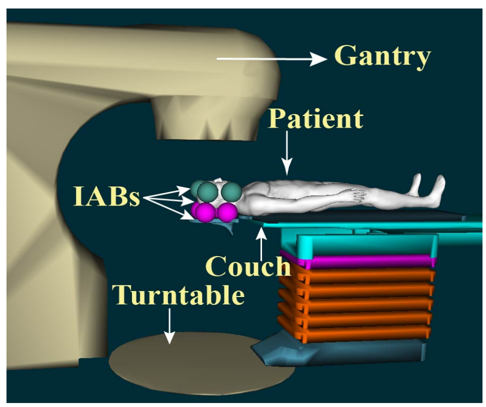


(b) Reproducing a nonlinear S-shape motion

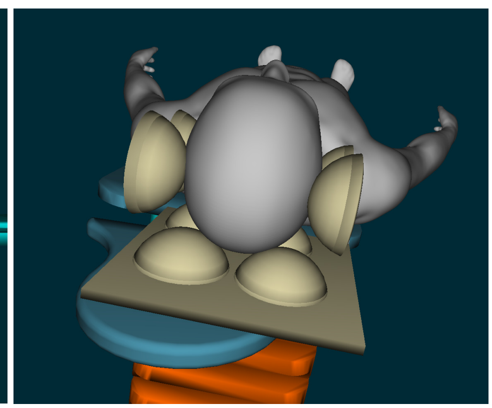
Figure 10: A CLF motion executor (red curves) that shows convergence to local attractors (green asterisks) and follows 3 different set trajectories (blue curves) for 2D nonlinear motion-trajectory problems on the WAM robot.



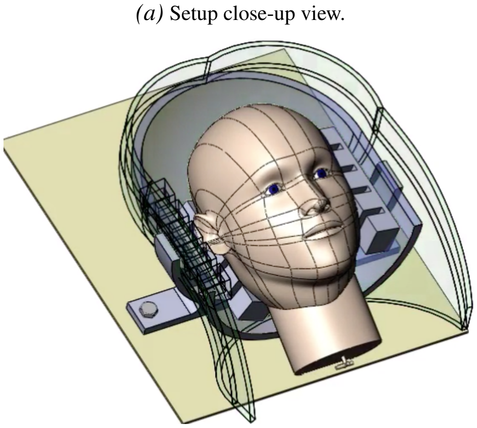
(a) Setup close-up view.



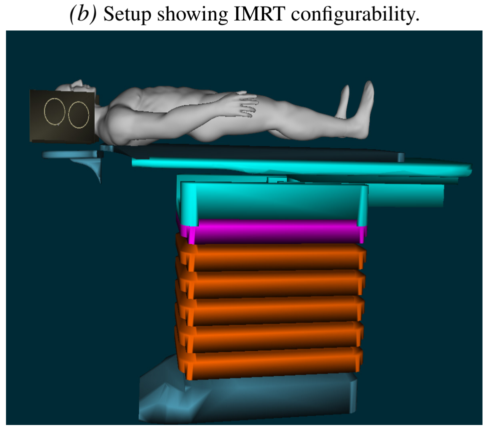
(b) Setup showing IMRT configurability.



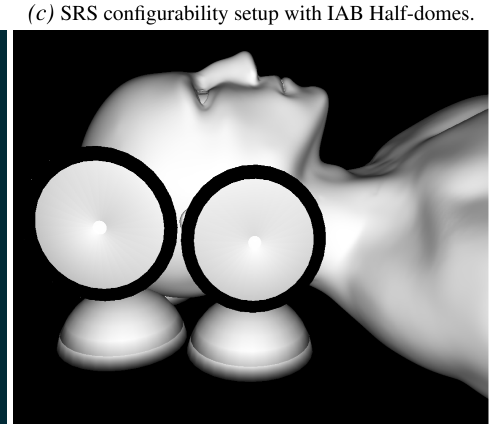
(c) SRS configurability setup with IAB Half-domes.



(d) Wearable setup under MRI Coils.



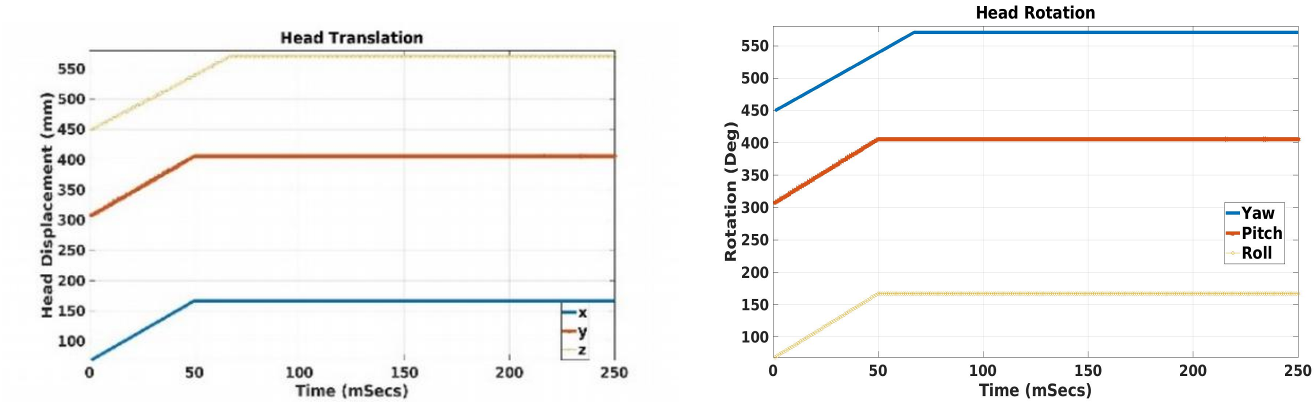
(e) Patient, IABs holders and couch.



(f) Patient-Robot System.

Figure 11: Proposed MRI-compatible LINAC patient motion compensation system.

Hypothesis.
Owing to the success of parallel robot mechanisms at precise manipulation tasks [2, 20, 66–68], **I hypothesize that a parallel soft-manipulator mechanism will yield the desired submillimeter and subdegree accuracy necessary for online, real-time head motion control in MRI-LINAC RT.**
Procedure.



(a) Translational motion. *(b)* Rotational motion.

Figure 12: Open-loop setpoint-following for patient's head motion in $\mathbb{SE}(3)$. Reprinted from [13].

A. Head Motion Correction in $\mathbb{SE}(3)$: I will systematically synthesize and analyze parallel soft robot manipulators for head and neck motion correction in MRI-LINAC systems. I will then leverage the kinematics and kinetics of soft manipulators which I proposed in [28] to construct the hierarchical motion planner in Aim II. Synthesizing multi-DOF parallel soft robots is challenging given the interdependency of the parameters that characterize the deformation, the individual robot constraints' relative three dimensional orientation, permitted motion orientations, the three dimensional relation between constraints and allowed motions, and the possibility of multiple assembly modes that may result in the same end-effector pose [66]. The configuration that shall be investigated shall consist of soft actuators so arranged that their independent or coupled actuation can produce the needed head motion correction along the left-right (LR), the anterior-posterior (AP) , and/or the ssuperior-inferior (SI) axes. I will analyze the manipulation map, kinematics and kinetics of the respective closed-loop chains, and analyze the contact equations between the IAB system and head.

Fig. 11b shows an example standalone motion correction prototype for an IMRT system while Fig. 11c shows the proposed mechanism for MRI-LINAC systems (without MRI coils). Owing to the modular design, the coils of an MRI can be easily integrated onto this mechanism. In a parallel kinematic manner, the soft domes are positioned around the patient's cranial region while the patient lies supine on a typical MRI/RT treatment couch (Fig. 11b). The soft domes will be held in place around the head by impact-resistant low-temperature rigid PVC foam insulation sheet that is encased in carbon fiber. Velcro stickers (not shown) will be affixed to the planar soft dome holders to accommodate different patient cranial geometry – thus providing a modularization that ensures re-usability for different patients. The side actuators will correct head motion along the LR axis of the head anatomy $i.e.$ (yaw and roll motions), while the bottom ones will correct head motion along the AP direction. The SI motion will be adjusted by the two lower actuators on the bottom of the neck. These will conform deformation in a non-Gaussian fashion through an appropriate configuration of fiber-reinforcing (see videos). The domes underneath the forehead would control pure z translation and pitch rotasry motions.

In preliminary work [28], I have synthesized differential kinematics [69], continuum mechanics [70,71] and multi-bodied kinematics. Equation (7) yields the cranial manipulation constraint between the soft actuators and the head so that we can find the respective translational and rotational head velocity components, v_h, ω_h respectively in world frames. We can easily find the pseudo inverse of the manipulation map, G in (7), so as to determine head velocity on the treatment couch. The derivation of this equation is detailed in [27].
B. Expected Results: I would expect that my results will follow the open-loop head motion control simulation results in the SOFA [72] framework as presented in my recently accepted publication [13] using the proposed setup of Fig. 11f: raising or rotating the head in $\mathbb{SE}(3)$ resulted in steady-state reference trajectory tracking along all 6-DoFs of head motion as shown in Fig. 12.

3.3.4 R_{00} Aim: Patient oncological clinical trials.

To verify accuracy of delivered dose, a complete end-to-end evaluation of the robotic MRI-compatible RT system will be conducted using anthropomorphic phantom studies. From the preliminary data (Fig. 3, 5, 12), whereupon excellent agreement was found between head motion and given target trajectory using the adaptive controller proposed in [20]. Once we ascertain the efficacy of this, we will move to healthy human volunteer trials.
Statistical Plan: Phantom-based and healthy human volunteer trials will be conducted after we finish the design and build of the proposed system. A complete end-to-end testing with 3D printed head phantoms containing dosimetric gel will be used to evaluate 3D radiation dose accuracy for both single and multiple target MRI-compatible RT plans. A 20 volunteer study with a mock radiation beam will be conducted in a clinical environment to verify 6DOF head control and patient safety systems. A clinical study on 20 whole brain patients will be performed where validation of method will be determined by a statistical endpoint defining success as to whether or not the 6D intracranial target is ≤ 0.5mm and $\leq 0.5°$ for greater than 95% of the treatment time.

4 Training in the Responsible Conduct of Research

University of Pennsylvania
Penn Engineering

School of Engineering and Applied Science
Department of Mechanical Engineering
and Applied Mechanics
272 Towne Building
220 South 33rd Street
Philadelphia, PA 19104-6315

Dr. James Pikul
Assistant Professor

Tel: 215.573.2786
Fax: 215.573.6334
pikul@seas.upenn.edu

May 21, 2020

Dear Selection Committee Members,

I am writing this letter to enthusiastically support Dr. Ogunmolu and his K99/R00 Pathway to Independence Award Application. Dr. Ogunmolu is a wonderful individual who combines excellence as a scholar, a passion to solve health challenges by applying engineering solutions, a bright and cheerful character, and leadership potential. I believe these qualities perfectly align Dr. Ogunmolu with the K99/R00 Pathway to Independence Award, as he will produce excellent fundamental research, realize important benefits for patients, and transition into a strong independent leader.

I have known Dr. Ogunmolu, who goes by ‘Lekan’, since the Fall of 2019 when he contacted me about collaborating on his project to stabilize patient heads during radiation therapy using soft robots. Since that time, I have had several conversations with Lekan and have been able to assess his competency as a researcher and vision for his proposed work, and I have been impressed. Lekan has shown a deep understanding of his field and also quickly learns new information, which makes him a great asset in cross-disciplinary research. Lekan has published work in the top robotics conferences, which shows his ability to plan and realize high quality research. I should mention that publication in these conferences, such as the IEEE International Conference on Robotics and Automation, is equivalent to publishing in a top field journal in the robotics community. This prioritization for conference publications is different than many fields, so I want to make it clear that Lekan has a strong publication record compared to other researchers at his level in the robotics community. Lekan’s invited talks to Open Robotics, Stanford University, and University of Chicago show that he is being recognized for his contributions and is an emerging leader. Lekan has also mentored six students, including two master’s theses. Overall, Lekan has a strong track record of research and mentoring success and a very promising trajectory that make him an excellent candidate for the K99/R00 Pathway to Independence Award.

I am the right mentor for Lekan because I can provide him with the technical advice required for his proposed research to succeed and I have recently started my own lab at the UPenn, so I have a breadth of recent and relevant experiences to share with Lekan. I am looking forward to discussing and supervising Lekan’s experimental designs and professional development. As an example of my professional success as an Assistant Professor, I am mentoring seven graduate students, two post-doctoral scholars, three master’s students (2 graduated), and twelve undergraduates. Fostering a creative research group with diverse experiences is important for me, which is why I have mentored seven female students and four underrepresented minority students. While growing my lab, my group and I have published 9 journal articles (One in *Nature*, several in 10+ IF journals), 5 refereed conference proceedings (one best paper award), and 3 patents applications. To fund this growth, I have led several successful grant proposals including three DARPA projects (one as PI, two as co-PI), an NSF Emerging Frontiers in Research and Innovation on soft robotics (PI), an NSF CAREER award (PI), and an ONR Young Investigator Program award (PI), which sum to total awards over $6,000,000. I have, additionally, contributed to my research community and University. I am leading the Formula-SAE Penn Electric Racing Team which placed 3rd in the nation last summer. I will apply my experience and accumulated knowledge as an Assistant Professor to mentor Lekan. In addition to mentoring Lekan to achieve his own version of success, I will introduce him to other faculty in my network whose work overlaps with Lekan’s interest, including the four co-PIs on my NSF EFRI grant that seeks to understand fundamental problems related to the soft devices that Lekan will use.

In summary, I strongly support Lekan’s application for the K99/R00 Pathway to Independence Award. He has the technical talent, experiences, and leadership to be a successful PI. This award will allow Lekan to realize his goals of applying engineering solutions and soft robotics to critical health problems, which will ultimately benefit many patients throughout his career.

Sincerely,

James H. Pikul