

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

Future Work

Publications

References

# Automating Treatment Planning in Radiation Therapy

Lekan Ogunmolu

Perelman School of Medicine

University of Pennsylvania, Philadelphia, PA

February 04, 2021

# Funding Sources

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



CANCER PREVENTION & RESEARCH  
INSTITUTE OF TEXAS

# Talk Outline

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues  
Approach

iDG Results

Future Work

Publications

References

- Beam Orientation Optimization (BOO)
  - Monte Carlo Tree Search and Neuro-Dynamic Programming for BOO
  - Column Generation as Pretraining for MCTS for BOO
- Patient Head Motion Correction in External Beam Radiation Therapy
  - Intensity-Modulated RT (IMRT): Earlier PhD Work
  - Magnetic Resonance Imaging and Linear Accelerator Systems (MRI-LINACs)
- Robustness Margins and Robust Deep Policies for Nonlinear Control

# Research Significance

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

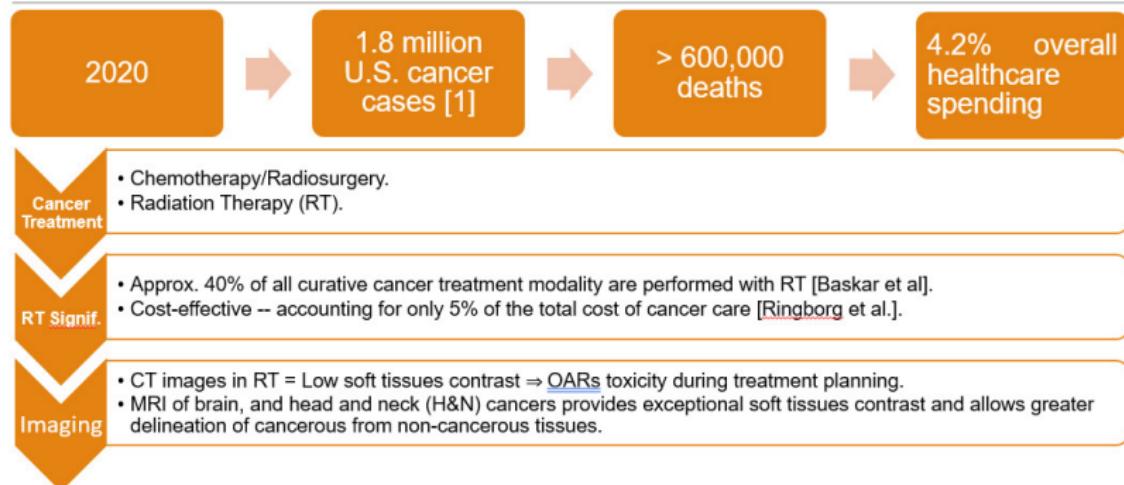
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



# IMRT Treatment Planning (Beam Delivery)

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

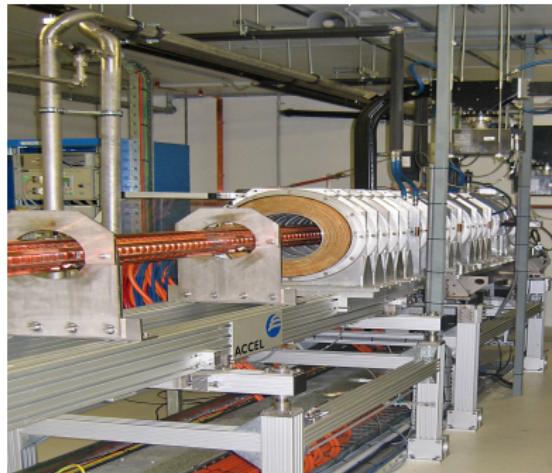
Approach

iDG Results

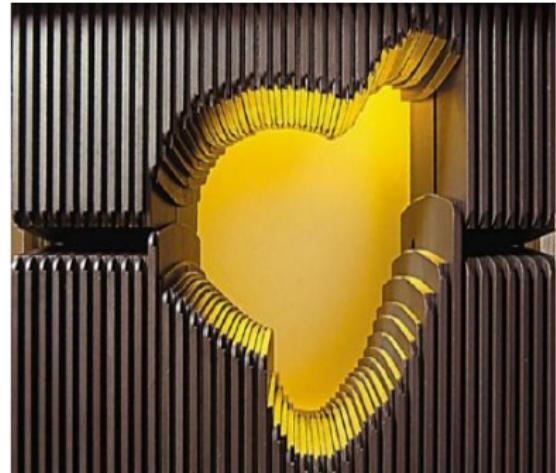
Future Work

Publications

References



The Australian Synchrotron.



Multi-leaf collimator (Varian)

# Radiation Delivery Couch and Gantry

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach

iDG Results

Future Work

Publications

References



Varian's TrueBeam Radiotherapy System.

# Part I.A: Beam Orientation Optimization (BOO)

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation  
Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

Future Work

Publications

References

## ■ Beam Orientation Optimization (BOO)

- Monte Carlo Tree Search and Neuro-Dynamic Programming for BOO

# Contributions

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS

BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work  
Publications

References

## Relevant Publications

Ogunmolu, Olalekan, Michael Folkerts, Dan Nguyen, Nicholas Gans, and Steve Jiang. "Deep BOO! Automating Beam Orientation Optimization in Radiation Therapy." In *Algorithm Foundations of Robotics XIII*, Merida, Mexico. Published in *Springer's Proceedings in Advanced Robotics (SPAR) Book*, 2020.

- A sparse tree lookout strategy for games with large state spaces guides transition between beam angle sets
- Tree lookout strategy guided by a deep neural network policy

# BOO Process: Fluence Map Optimization

Automating Treatment Planning in Radiation Therapy

Lekan Ogunmolu

BOO

MCTS

BOO Motivation

Approach

Head Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

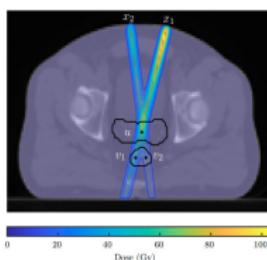
Future Work

Publications

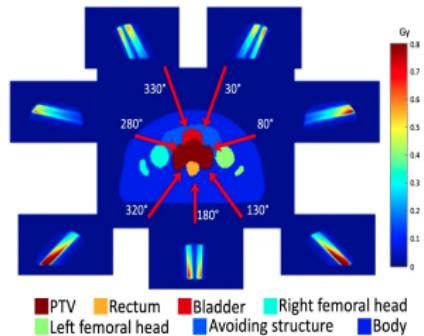
References



Prostate CT slice



Prostate before  
BOO



Fluence Map

# Treatment Plan Flowchart

Automating  
Treatment  
Planning in  
Radiation  
Therapy

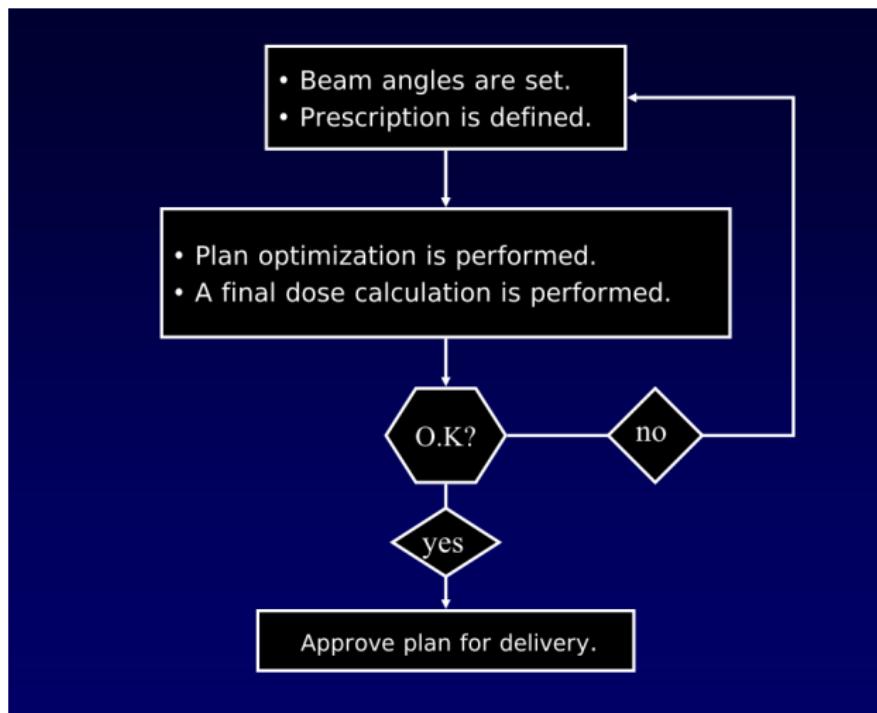
Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



Reprinted from "IMRT Optimization Algorithms. David Shepard. Swedish Cancer Institute. AAPM 2007."

# Current Approaches

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS

BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach

iDG Results

Future Work  
Publications

References

- Stochastic optimization approaches: simulated annealing; genetic algorithms and gradient search, or a combination of genetic and gradient search algorithms.
- Mixed-integer programming, branch and cut/bound algorithms, beam angle elimination algorithms.
- Commercial planners use some highly non-convex objective (actual function is proprietary and unknown to public).

# IMRT/BOO Motivation

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

- Beam orientations largely manually chosen or adopted from a standard protocol for clinical use.
- Pre-solve the dose influence matrices for each beam orientation.
- Then solve FMO.
- Time consuming (hours for dose fluence), and minutes for (FMO); Still solution is often not optimal.

# Approach

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach  
Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

- A Tower Neural Network generates a policy that guides MCTS simulations for two players in a zero-sum Markov game
  - Produces a *utility (value) function* & a subjective *probability distribution*
- Each player in a two-player Markov game finds an alternating best response to the current player's average strategy
  - driving the neural network policy's weights toward an approximate **saddle equilibrium** [Heinrich et al. (2015)].
  - aids network in finding an *approximately optimal* beam angle candidate set that meets a dosimetric requirements.

# Data Preprocessing

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

Future Work

Publications

References

- 77 anonymized patient CT scans,  $D$ , and their dose influence matrices,  $\mathcal{D}_{ij}$
- Scans shaped,  $D \times N \times H \times W$  from prostate cases in previous treatment plans
- Each slice resized to  $64 \times 64$

# State Representation: Prostate Organ Masks

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

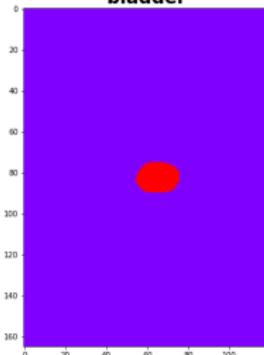
Robustness issues  
Approach

iDG Results

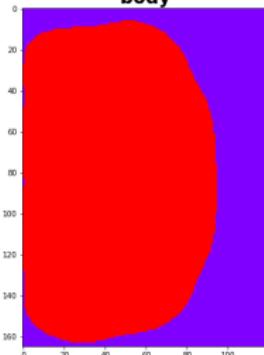
Future Work  
Publications

References

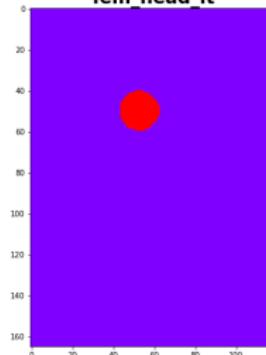
bladder



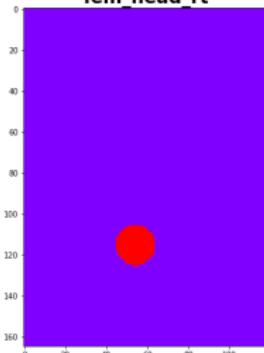
body



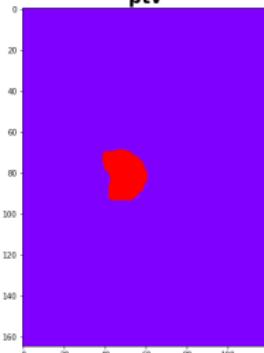
fem\_head\_lt



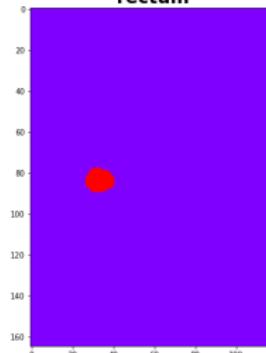
fem\_head\_rt



ptv



rectum



# State Representation: Beam Angles

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

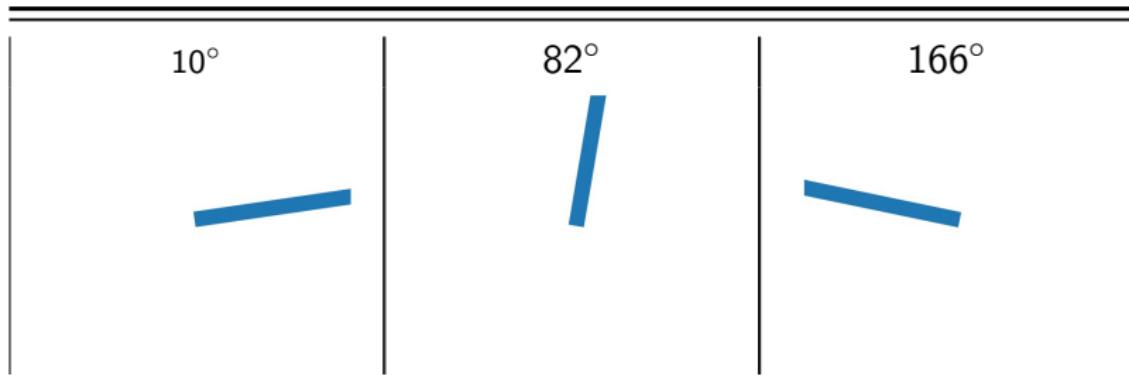
BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

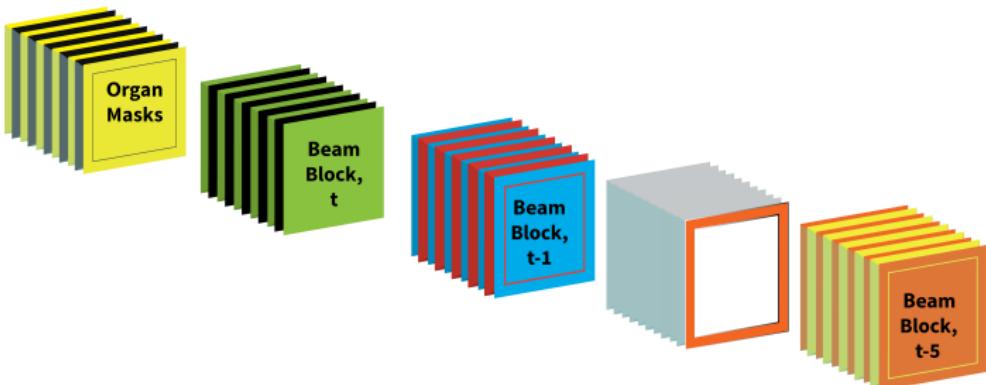
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

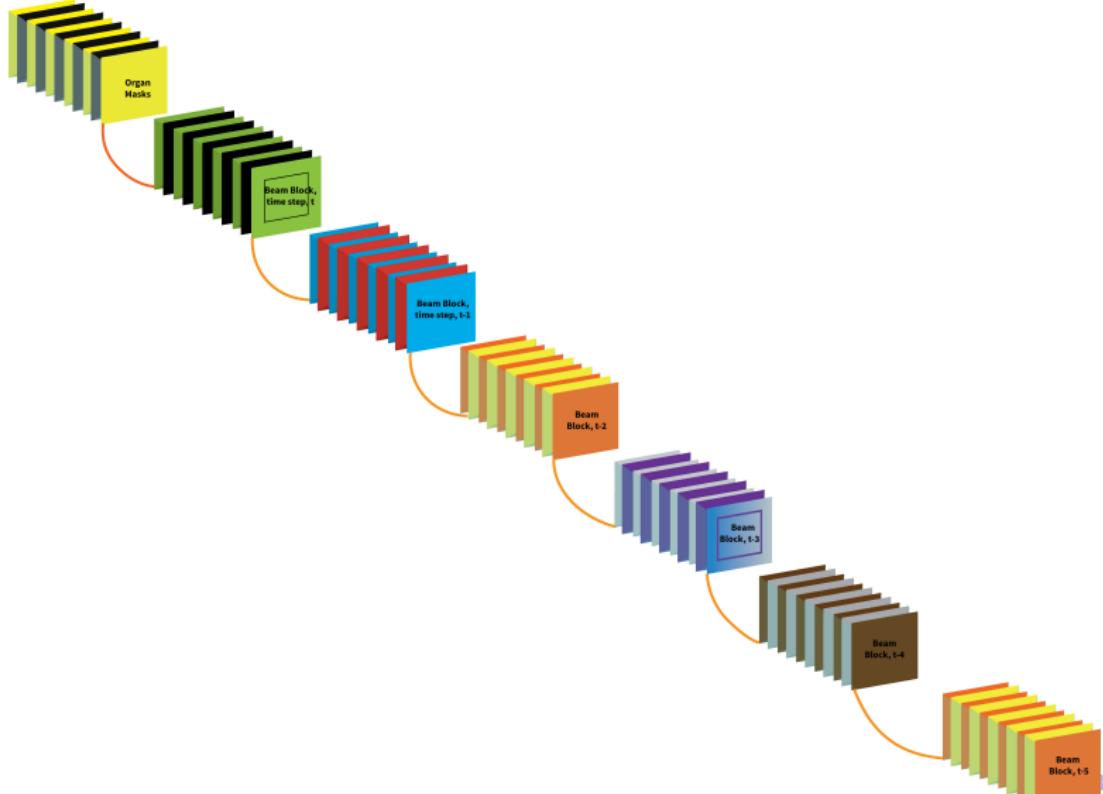
Future Work  
Publications  
References



# State Representation



# State Representation



# Tree Representation and Game Simulation

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

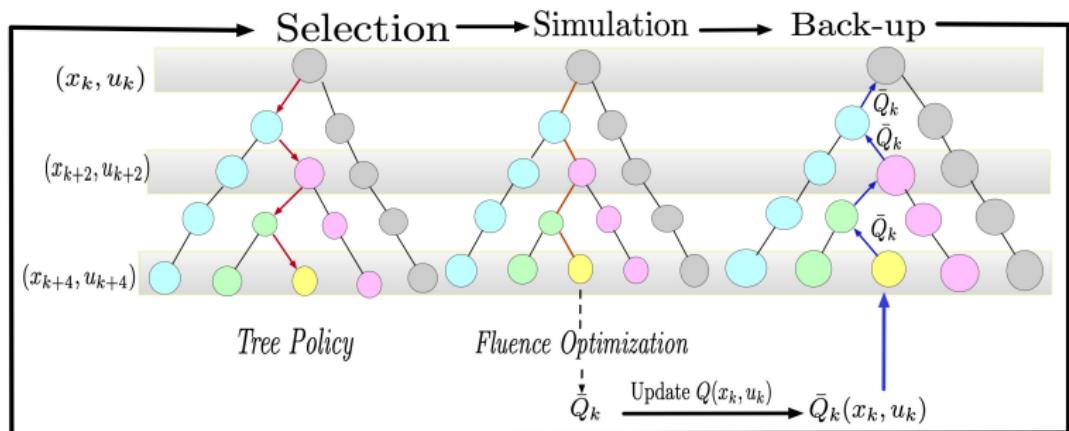
BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



# Tree Composition

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications

References

Every **node** of the tree,  $x$ , has the following fields:

- a pointer to the parent that led to it,  $x.p$ ;
- the beamlets,  $x_b$ , stored at that node;  $b = \{1, \dots, m\}$ ;
- a set of move probabilities prior,  $p(s, a)$ ;
- a pointer  $x.r$ , to the reward  $r_t$ , for the state  $x_t$ ;
- a pointer to the state-action value  $Q(s, a)$  and its upper confidence bound  $U(s, a)$ ;
- a visit count  $N(s, a)$ , that indicates the number of times that node was visited; and
- a pointer  $x.child$ ; to each of its children nodes.

# Game Simulation: Mixed Strategies

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

- Each player,  $p_1, p_2$ , bases its decision on a random event's outcome
  - generating a **mixed strategy** determined by **averaging the outcome** of individual plays.
- Both players constitute a two-player **stochastic action selection strategy**:  $\pi(s, a) = Pr(a|s) := \{\pi^{p_1}, \pi^{p_2}\}$  that gives the probability of selecting moves in any given state
- Suppose the game simulation starts from an initial condition  $s_0$ .

# Saddle Point Strategy Formulation

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work  
Publications

References

- The **saddle point strategies** for an optimal control sequence pair  $\{a_t^{p_1^*}, a_t^{p_2^*}\}$  can be recursively obtained by optimizing a state-action value cost,  $\mathcal{J}_t(s, a)$

$$V_t^*(s) = Q_t^*(s_t, \pi_t^{p_1}, \pi_t^{p_2}) = \min_{\pi^{p_1} \in \Pi^{p_1}} \max_{\pi^{p_2} \in \Pi^{p_2}} Q_t^*(s_t, \pi^{p_1}, \pi^{p_2}) \\ \forall s_t \in \mathcal{S}, \pi^{p_1} \in \Pi^{p_1}, \pi^{p_2} \in \Pi^{p_2}.$$

such that

$$v_{p_1}^* \leq v^* \leq v_{p_2}^* \quad \forall \{\pi_t^{p_1}, \pi_t^{p_2}\}_{0 \leq t \leq T}.$$

where  $v_{p_i}^*$  are the respective optimal values for each player.

# Fluence Map Optimization

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work

Publications

References

- $\mathcal{X} \implies$  total discretized voxels of interest (*VOI's*) in a target volume
- $\mathcal{B}_1 \cup \mathcal{B}_2 \cup \dots \cup \mathcal{B}_n \subseteq \mathcal{B} \implies$  beam partition subset
- $\mathcal{D}_{ij}(\theta_k) \implies$  matrix that describes each dose influence,  $d_i$ 
  - Computed by calculating each  $d_i$  for every bixel,  $j$ , at every  $\varphi^\circ$ , resolution, where  $j \in \mathcal{B}_k$

# Methods: FMO problem definition

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References

## ■ Cost

$$\frac{1}{v_s} \sum_{s \in \text{OARs}} \|(\underline{b}_s - \underline{w}_s \mathcal{D}_{ij}^s \mathbf{x}_s)_+\|_2^2 + \frac{1}{v_s} \sum_{s \in \text{PTVs}} \|(\bar{w}_s \mathcal{D}_{ij}^s \mathbf{x}_s - b_s)_+\|_2^2 \quad (1)$$

## ■ Pre-calculated dose term: $\mathbf{Ax} = \{\sum_s \frac{w_s}{v_s} \mathcal{D}_{ij}^s \mathbf{x}_s \mid \mathcal{D}_{ij} \in \mathbb{R}^{n \times l}, n > l\}$

# Methods: FMO

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues

Approach

iDG Results

Future Work

Publications

References

- Rewriting the objective

$$\min \frac{1}{2} \|Ax - b\|_2^2 \quad \text{subject to } x \geq 0.$$

- With Lagrangian:

$$L(x, \lambda) = \min \frac{1}{2} \|Ax - b\|_2^2 - \lambda^T x.$$

- Introducing an auxiliary variable  $z$ , we have

$$\min_x \frac{1}{2} \|Ax - b\|_2^2, \quad \text{subject to } z = x, \quad z \geq 0,$$

# Methods: FMO by way of ADMM

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

Future Work

Publications

References

- Solving either the  $\mathbf{x}$  and  $\mathbf{z}$  sub-problems, we have

$$\mathbf{x}^{k+1} = (\mathbf{A}^T \mathbf{A} + \rho \mathbf{I})^{-1} (\mathbf{A}^T \mathbf{b} + \rho \mathbf{z}^k - \boldsymbol{\lambda}^k). \quad (2)$$

- And using the soft-thresholding operator,  $S_{\boldsymbol{\lambda}/\rho}$ , we find that

$$\mathbf{z}^{k+1} = S_{\boldsymbol{\lambda}/\rho} (\mathbf{x}^{k+1} + \boldsymbol{\lambda}^k), \quad (3)$$

where  $S_{\boldsymbol{\lambda}/\rho}(\tau) = (\mathbf{x} - \boldsymbol{\lambda}/\rho)_+ - (-\tau - \boldsymbol{\lambda}/\rho)_+$ .  $\boldsymbol{\lambda}$  is updated as

$$\boldsymbol{\lambda}^{k+1} = \boldsymbol{\lambda}^k - \gamma (\mathbf{z}^{k+1} - \mathbf{x}^{k+1}), \quad (4)$$

where  $\gamma$  is a parameter that controls the step length.

# Training and Validation Loss

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

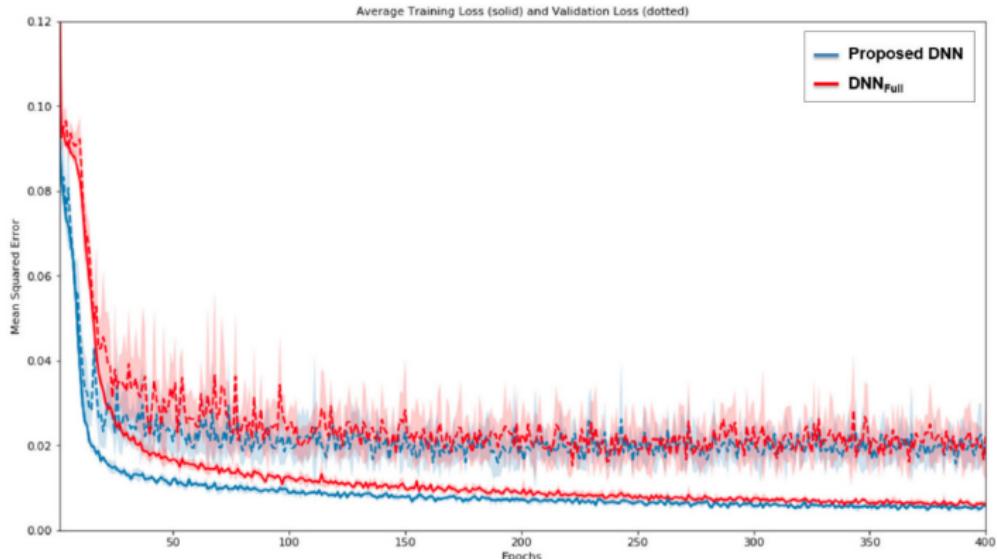
Approach

iDG Results

Future Work

Publications

References



*Average training (solid) and validation (dotted) loss function (MSE) values across six cross-validation folds for the network (blue) and full network.*

# BOO Results: Testing of self-play network

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

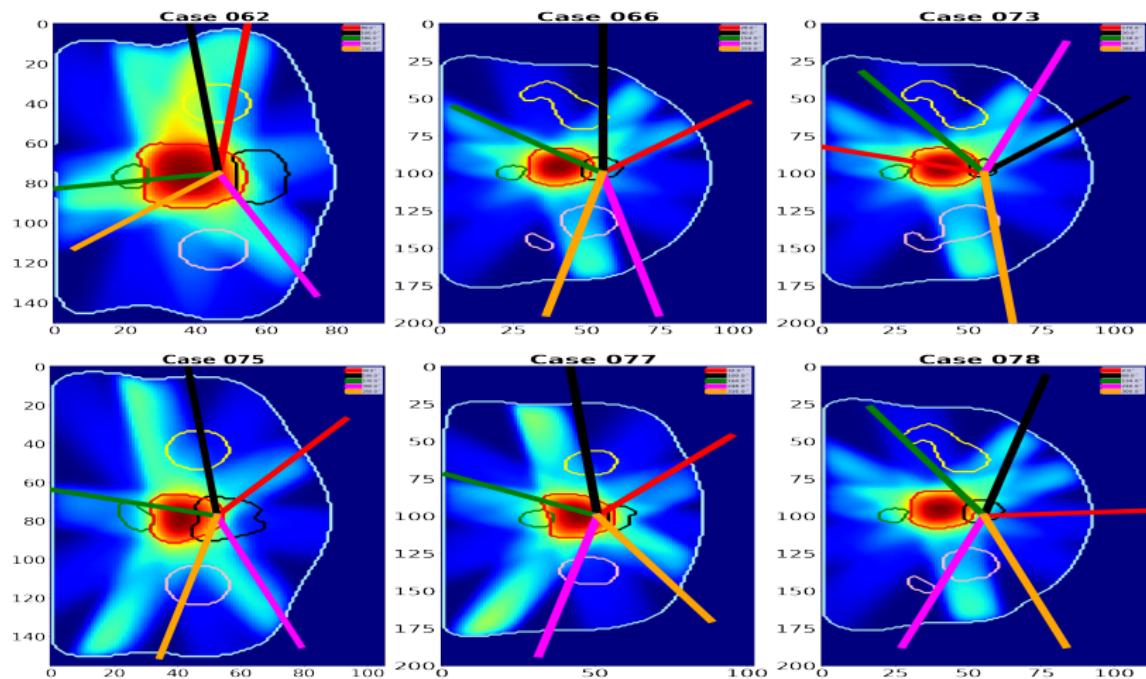
BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



# Dose Washes of Column Generation vs Neural Network

Automating Treatment Planning in Radiation Therapy

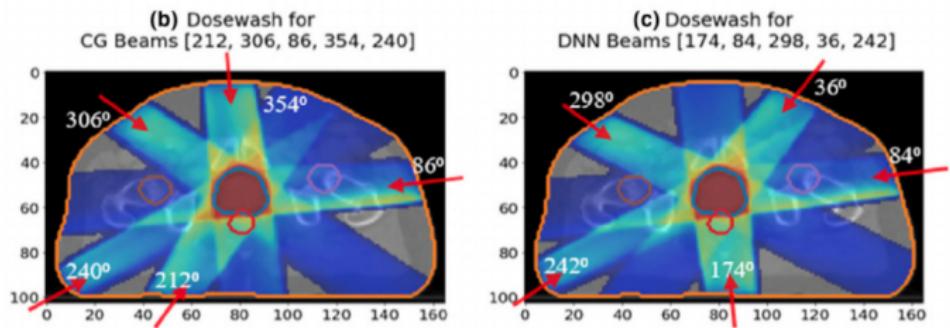
Lekan Ogunmolu

BOO  
MCTS  
BOO Motivation Approach

Head Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues Approach  
iDG Results

Future Work  
Publications  
References



Dose-Volume Histogram of CG vs DNN architectures [Sadeghnejad Barkousaraie, Azar and Ogunmolu, Olalekan and Jiang, Steve and Nguyen, Dan (2019)].

# Dose Volume Histograms

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT

MRI-LINAC

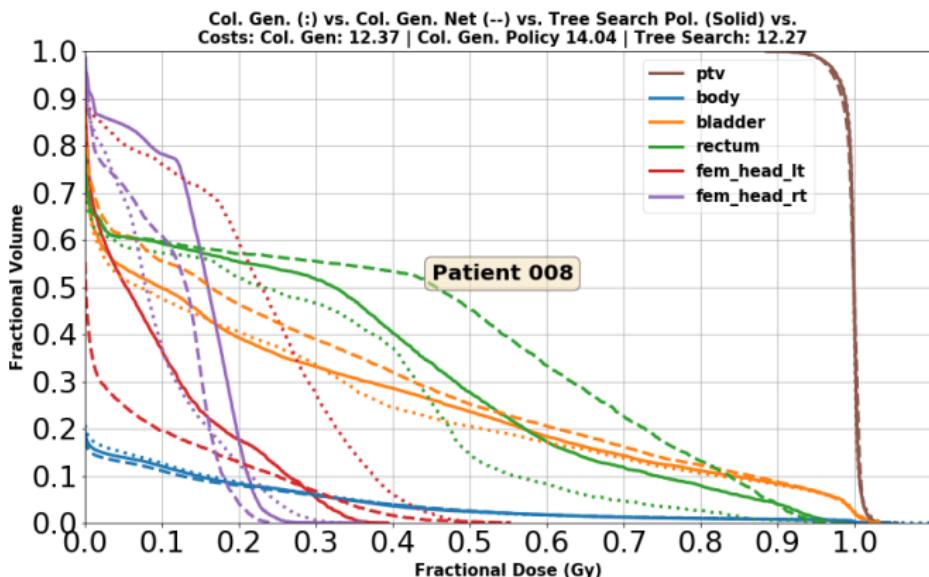
iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References



# Conclusions

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

- Finding the good beam angle candidates is orders of magnitude faster than the current approaches
  - Based on a neural network generative model of an MDP
  - Sparse lookahead search builds tree with nodes labeled by state-action pairs in an alternating manner (2-3 minutes).
  - Tree built stagewise from root to nodes has fixed depth; sample rewards stored on edges connecting state-action with state nodes
- Beam angles prediction takes between 2-3 minutes with MCTS vs 1 minute with Column Generation Pretraining.

# Head Stabilization in Radiation Therapy (RT)

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

- Head Stabilization in Cancer Radiation Therapy
  - Intensity-Modulated RT (IMRT)

# Varian's TrueBeam Radiotherapy System.

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation

Approach

Head  
Stabilization  
IMRT

MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References



# Correcting Head Motion: RT and MRI-LINACs

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



(a) The BRW SRS Frame [Chelvarajah et al. (2004)]



(b) Thermoplastic masks



(c) Frame With MRI Coils (PSOM)

# 4-D Motion Correction Stage

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

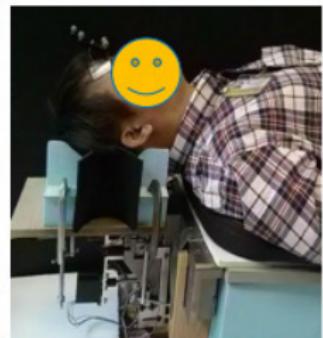
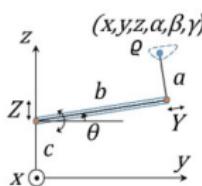
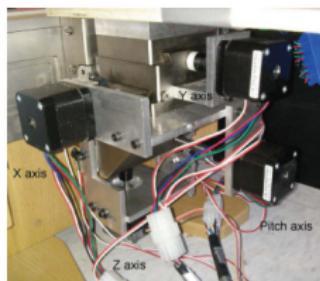
Approach

iDG Results

Future Work

Publications

References



Liu et al. (2015)

# 4-DOF Motion Controller Block Diagram

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

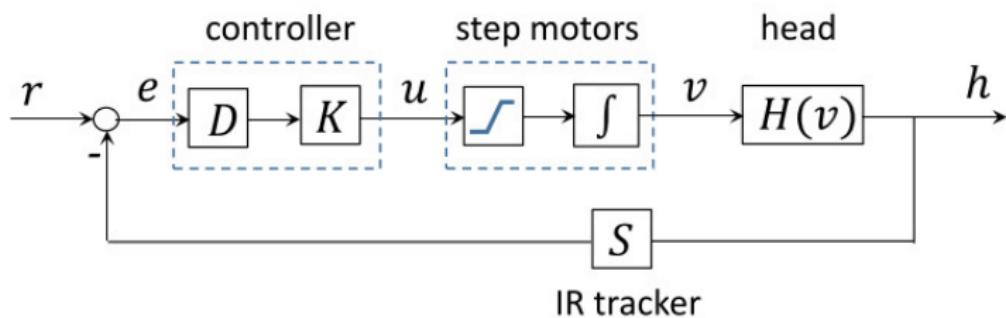
Robustness issues  
Approach

iDG Results

Future Work

Publications

References



Liu et al. (2015)

# Phantom Feedback Motion Correction Results

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

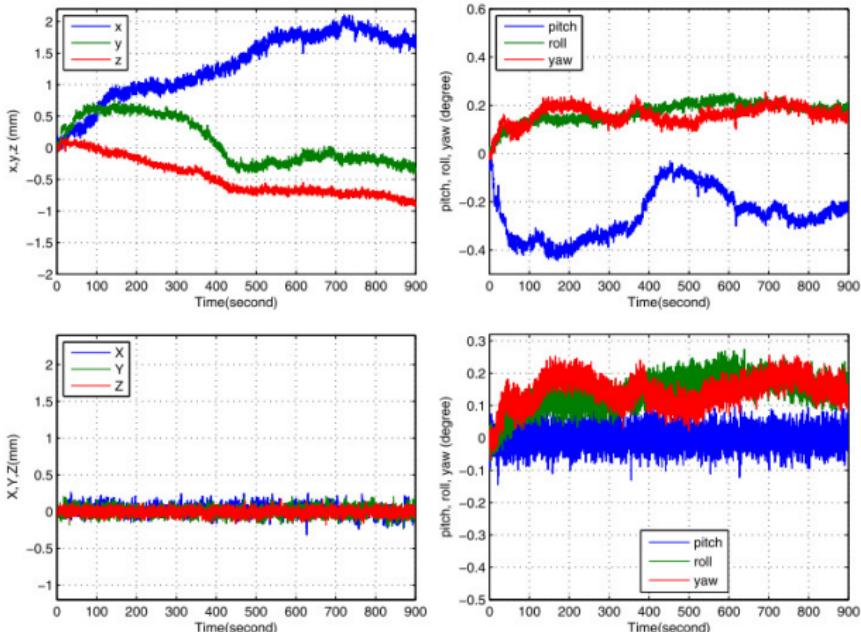
BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



Time response of feedback control without (left) and with (right) decoupling control [Liu et al. (2015)].

# Human Volunteer Feedback Motion Correction Results

Automating Treatment Planning in Radiation Therapy

Lekan Ogunmolu

BOO

MCTS

BOO Motivation Approach

Head Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

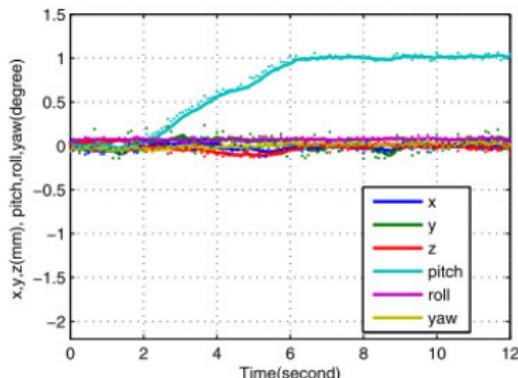
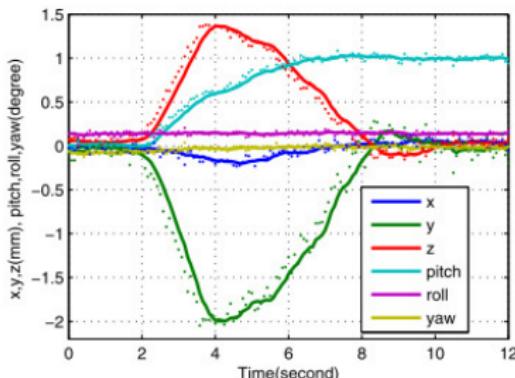
Approach

iDG Results

Future Work

Publications

References



Head Motion Without and With Motion Correction. Left: Coupled Axes; Right: Decoupled Axes.

# SRS: Wiersma Stewart-Gough Platform

Automating Treatment Planning in Radiation Therapy

Lekan Ogunmolu

BOO

MCTS

BOO Motivation Approach

Head Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

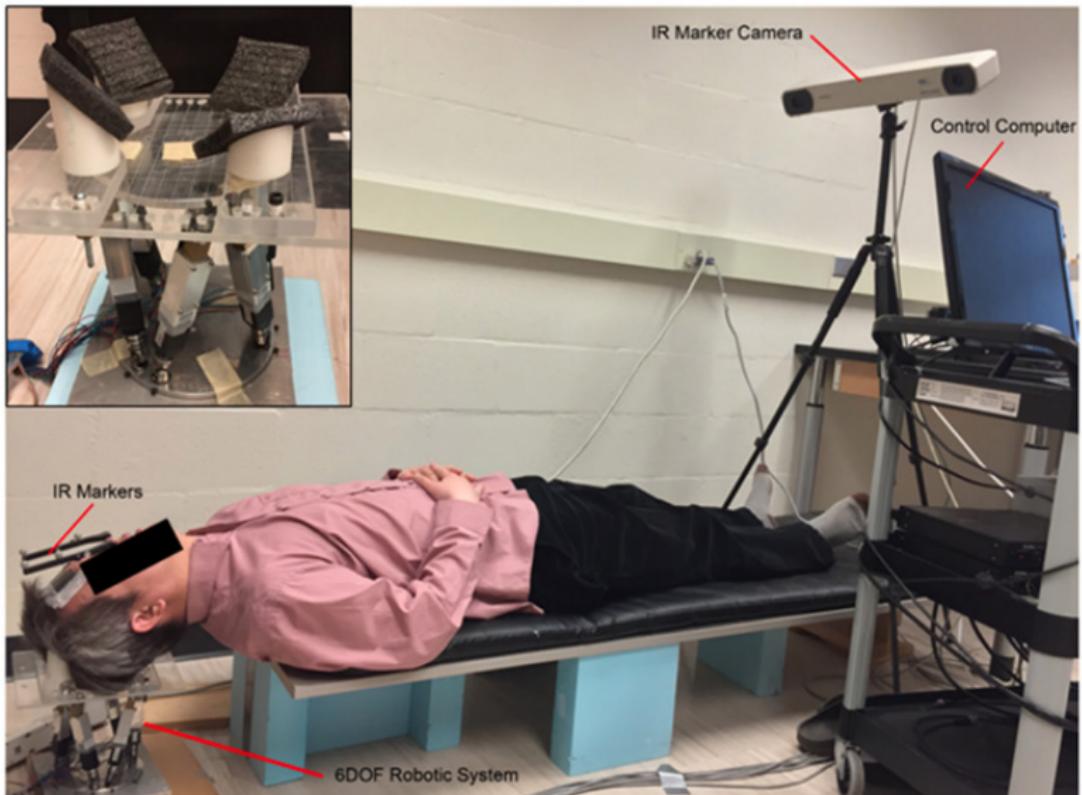
Approach

iDG Results

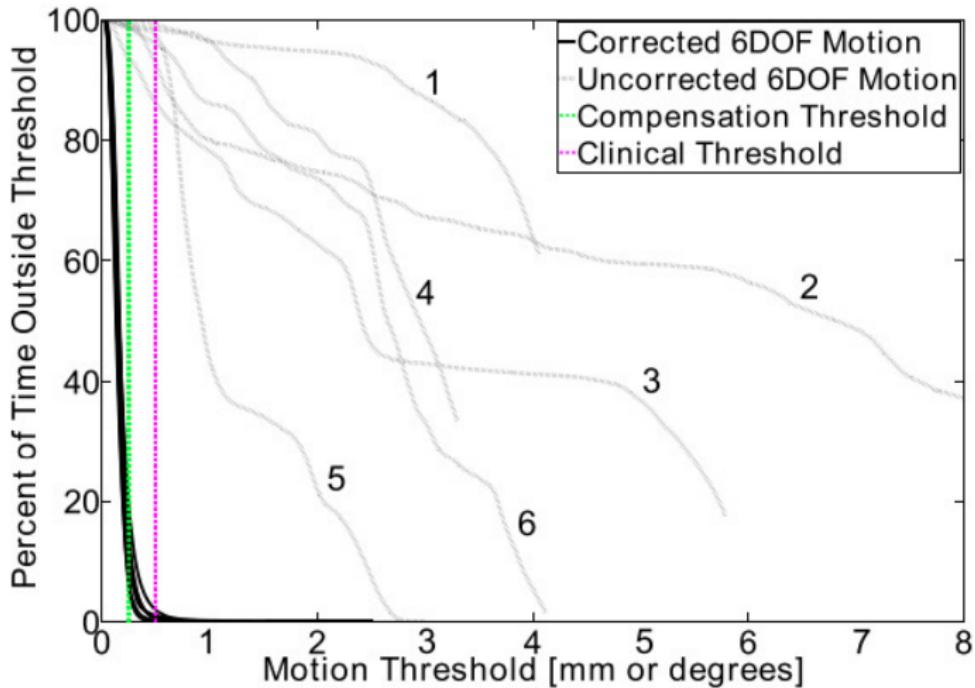
Future Work

Publications

References



# 6-DOF Motion Correction Results



# Drawbacks of current solutions

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References

- Rigid patient's body assumption
- Non-compliant immobilization devices
- Invasiveness during radiosurgery/RT
- Attenuation of photon beams

# Robotic Radiosurgery

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

Future Work

Publications

References



## A Patient Head Motion-Correction Mechanism for MRI-LINAC RT

OLALEKAN OGUNMOLU

DEPARTMENT OF RADIATION ONCOLOGY, PENN SCHOOL OF MEDICINE

- Current Collaborators: Rodney Wiersma & Xinmin Liu (UChicago → UPenn)
- Past Collaborators: Steve Jiang, Xuejun Gu, (UT Southwestern); Nick Gans (UT Dallas, UT Arlington)

# Radiation Delivery Couch and Gantry

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References



Varian's TrueBeam Radiotherapy System.

# Next-Gen RT Treatment with MRI-LINACs

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation

Approach

Head  
Stabilization  
IMRT

MRI-LINAC

iDG

Robustness issues

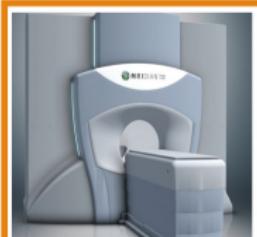
Approach

iDG Results

Future Work

Publications

References



## MRI in LINAC RT

- Next generation precision beam delivery.
  - High speed, high resolution MLC.
  - Online plan adaptation capabilities.
- 
- MRI that offers superior soft tissues visualization integrated with linear accelerator (LINAC) RT Offers univolved, online, and real-time cancer RT treatment [Raaymakers et al., Raaymakers et al.]
  - Commercialized in systems such as
    - Elekta AB's (Sweden) 1.5T diagnostic imaging system [Raaymakers et al.];
    - Viewray's MRIdian system [Motic et al.]; or
    - the MagnetTx's (Canada) Aurora RT system [Fallone et al.] among others.
  - Random and involuntary patient motion often occurs during image acquisition leading to
    - Artifacts → Poor image quality.
    - Incomplete irradiation of the tumor target.
    - Exposure of healthy tissues to radiation toxicity.
      - ❖ These lower the accuracy of online and real-time precise radiation dose delivery.
      - ❖ Affects clinical efficacy.

# Pneumatic Actuated Soft Robots for Head Motion Compensation

Automating Treatment Planning in Radiation Therapy

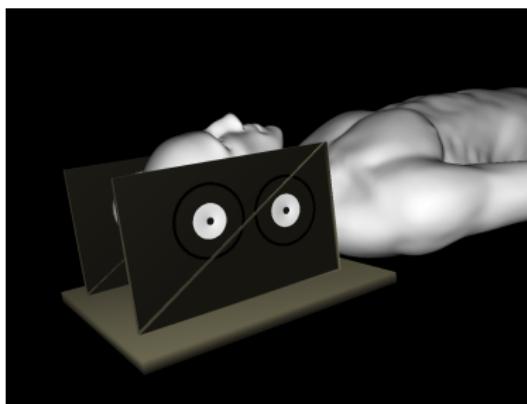
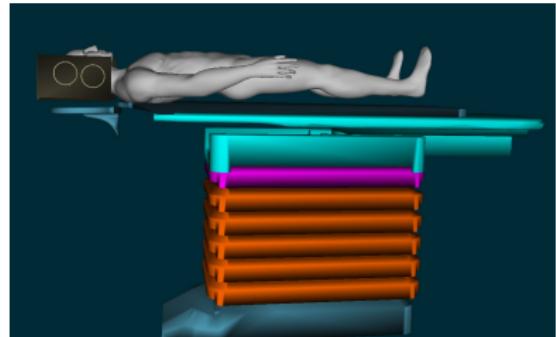
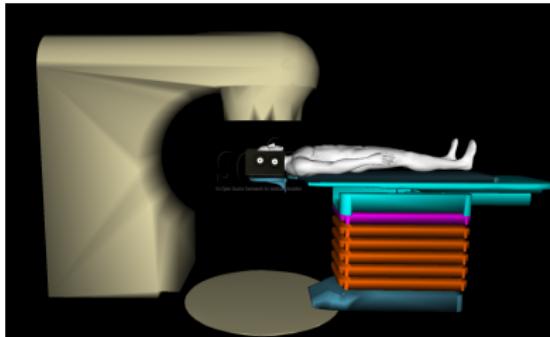
Lekan Ogunmolu

BOO  
MCTS  
BOO Motivation Approach

Head Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



# Cephalopods-inspired CCOARSE Actuator Design

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

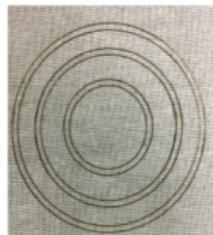
BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

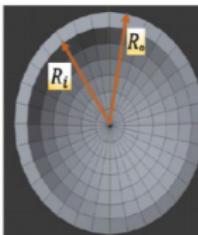
Circumferentially Constrained And Radially Symmetric Elastomers [Pikul et al. (2019)].



(a) Laser-Cut Fiber



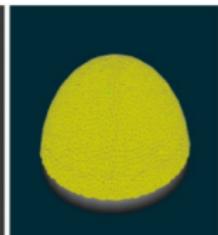
(b) Fiber+Rubber



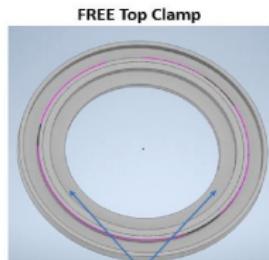
(c) Deformation Model



(d) Actuator+PVC Base



(e) Finite Element Model



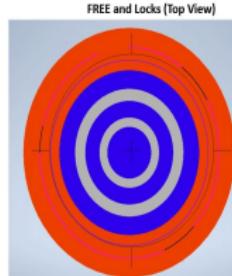
FREE Holder

FREE Top Clamp

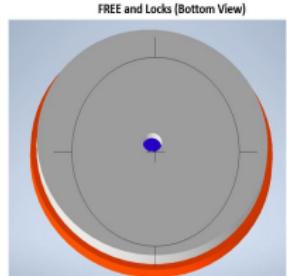


Push-to-Connect Fitting Hole

(f,g)



FREE and Locks (Top View)



FREE and Locks (Bottom View)

(h)

# CCOARSE Actuator Schematic

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation

Approach

Head  
Stabilization  
IMRT

MRI-LINAC

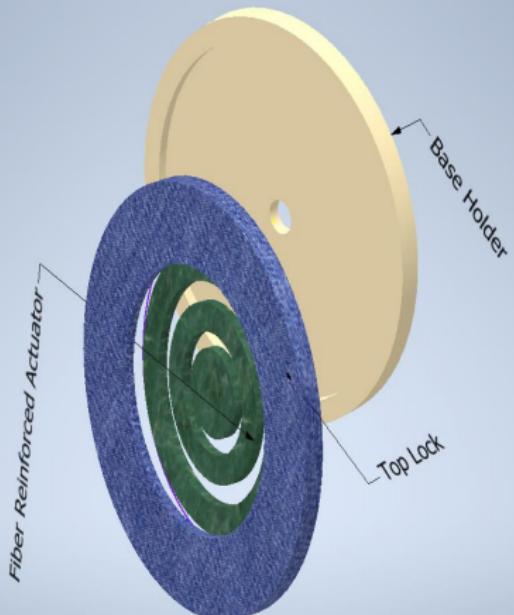
iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References



# Nonlinear Elastic Deformation Analysis

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

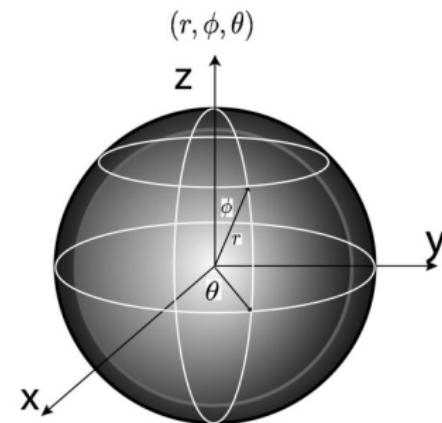
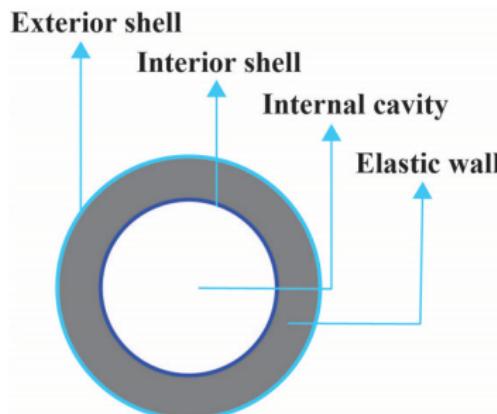
BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

## IAB SHELLS AND AIR CAVITY/DEFORMATION ANALYSIS



$$r_i \leq r \leq r_o, \quad 0 \leq \theta \leq 2\pi, \quad 0 \leq \phi \leq \pi$$

# Soft IK via Boundary Value Problem

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach  
Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results  
Future Work  
Publications  
References

- Using the following boundary conditions for the Cauchy Stress,
  - $\sigma_{rr}|_{R=R_0} = -P_{atm}, \sigma_{rr}|_{R=R_i} = -P_{atm} - P$
- And together with Cauchy's first law, we find that
  - $\sigma_{rr}(r) = - \int_{r_i}^{r_o} [2C_1\left(\frac{r}{R^2} - \frac{R^4}{r^5}\right) + 2C_2\left(\frac{r^3}{R^4} - \frac{R^2}{r^3}\right)] dr$
  - $\sigma_{rr}(r) = \int_{R_i}^{R_o} [2C_1\left(\frac{1}{r} - \frac{R^6}{r^7}\right) - 2C_2\left(\frac{R^4}{r^5} - \frac{r}{R^2}\right)] dr$
- With  $\sigma_{rr}|_{R=R_i} = -P_{atm} - P$  and setting  $P_{atm} = 0$ , we find
  - $P(r) = \int_{r_i}^{r_o} [2C_1\left(\frac{r}{R^2} - \frac{R^4}{r^5}\right) + 2C_2\left(\frac{r^3}{R^4} - \frac{R^2}{r^3}\right)] dr$
  - $P(r) = \int_{R_i}^{R_o} [2C_1\left(\frac{1}{r} - \frac{R^6}{r^7}\right) - 2C_2\left(\frac{R^4}{r^5} - \frac{r}{R^2}\right)] dr$
  - $r^3 = R^3 + r_i^3 - R_i^3$  and  $r_o^3 = R_o^3 + r_i^3 - R_i^3$

# Volumetric Deformation Results (Simulation)

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

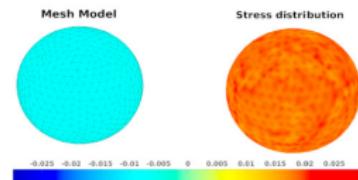
Approach

iDG Results

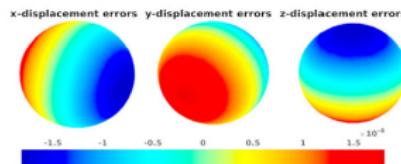
Future Work

Publications

References



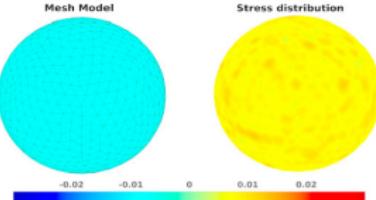
(a) Left: Mesh model. Right: Stress distribution on outer skin.



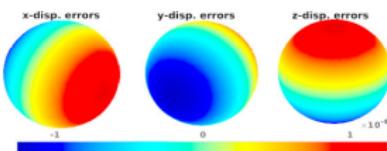
(b) Displacement errors along  $x, y, z$  coordinates.

Inputs				Outputs			
$C_1$	$C_2$	$R_i$	$r_i$	$R_o$	$r_o$	$P$	$\Delta V$
1.1e4	2.2e4	.027	.03	.03	.033	.76	$\approx 0$

Fig. 6: Volumetric Deformation (Expansion).



(a) Left: Mesh model. Right: Stress distribution on outer skin.



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

Inputs				Outputs			
$C_1$	$C_2$	$R_i$	$r_i$	$R_o$	$r_o$	$P$	$\Delta V$
1.1e4	2.2e4	.025	.03	.03	.028	-.34	$\approx 0$

Fig. 7: Volumetric Deformation (Compression).

# Pneumatic Control and Deformation Scheme

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

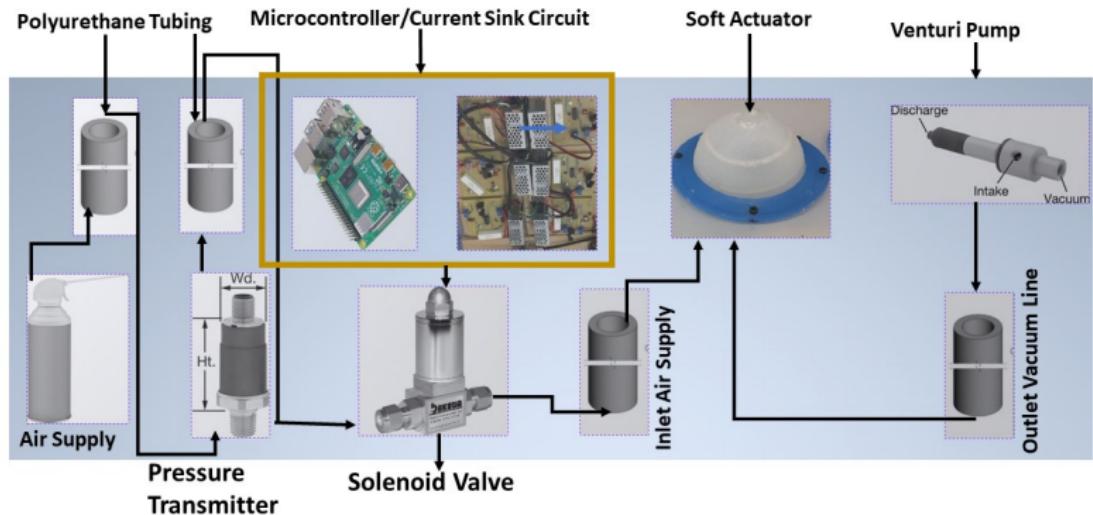
Approach

iDG Results

Future Work

Publications

References



# Volumetric Deformation Results (Actual)

Automating  
Treatment  
Planning in  
Radiation  
Therapy

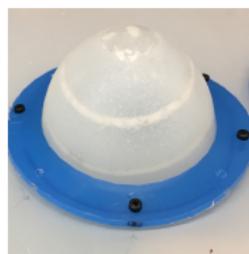
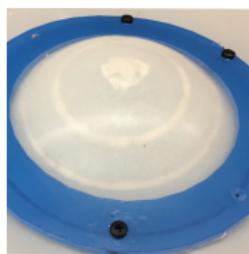
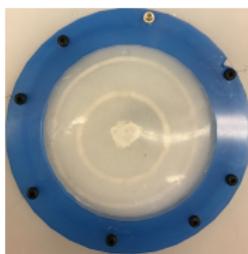
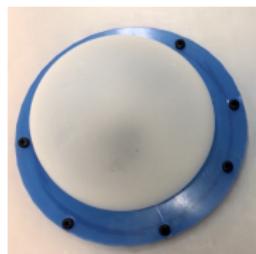
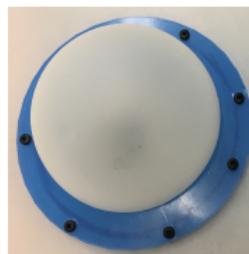
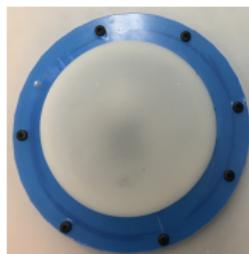
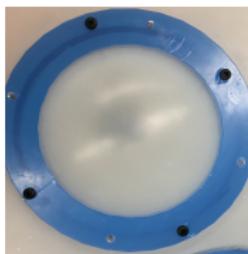
Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



# Mechanism Setup

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References



# Mechanism Setup with Phantom

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References



# Head Motion Control (Independent Actuation)

Automating  
Treatment  
Planning in  
Radiation  
Therapy

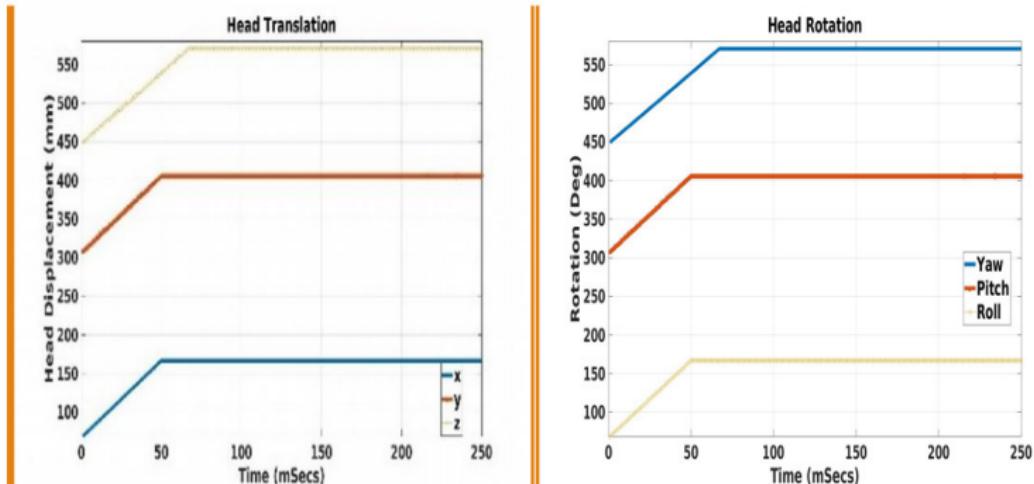
Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



Head Translation along  $x, y, z$  for a task of raising the head by a certain threshold above the table

Head rotation in Euler angles for a task of tilting the head about the  $x, y, z$  axes on the treatment table.

# Ongoing Work: 6-DOF Closed-loop Control

Automating  
Treatment  
Planning in  
Radiation  
Therapy

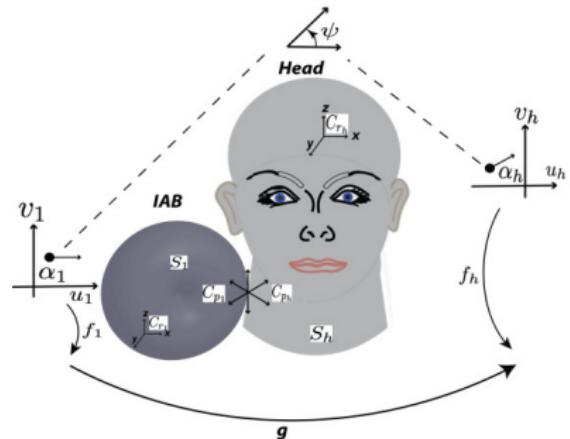
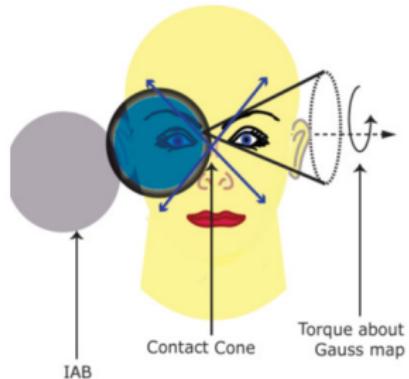
Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach  
Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

Continuum Mechanical Model Validation/Differential Geometry/Newton-Euler Dynamics



# Pneumatic Actuated Soft Robots for Head Motion Compensation

Automating Treatment Planning in Radiation Therapy

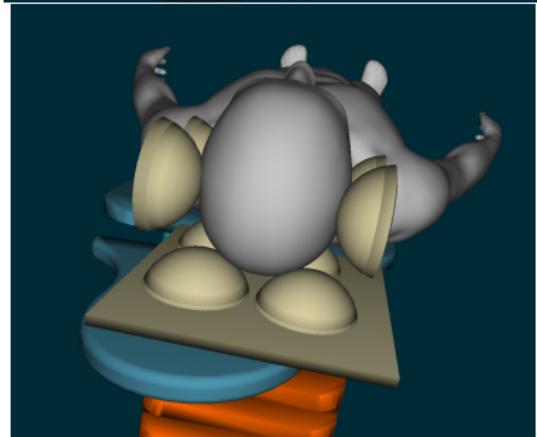
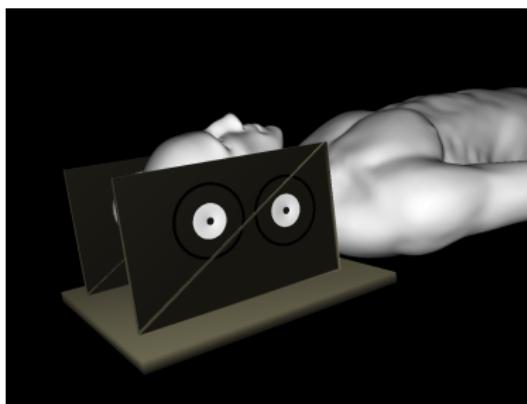
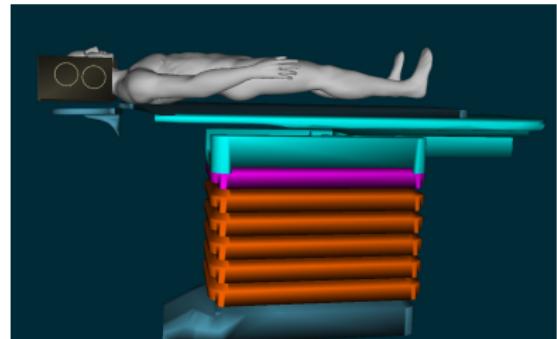
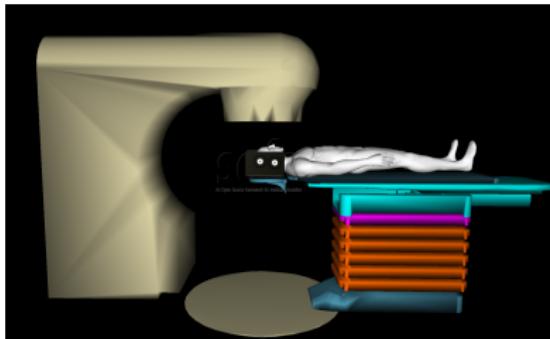
Lekan Ogunmolu

BOO  
MCTS  
BOO Motivation Approach

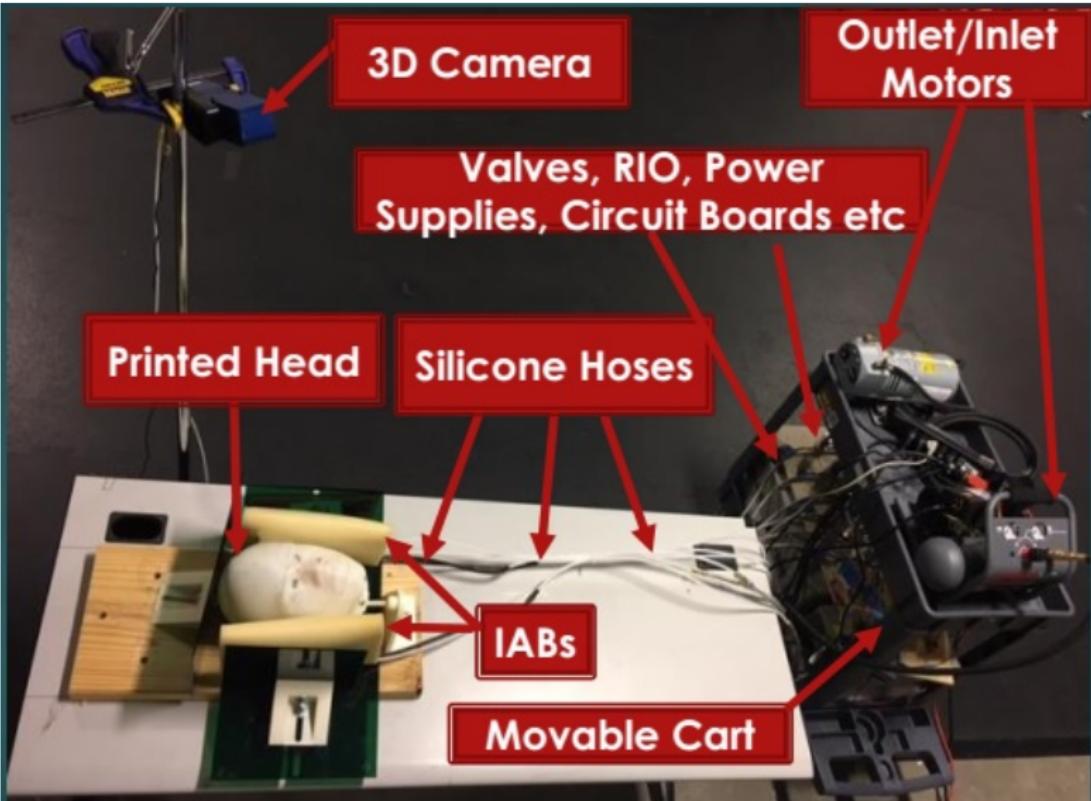
Head Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



# 3-DOF Simulation Testbed



Automating Treatment Planning in Radiation Therapy

Lekan Ogunmolu

BOO

MCTS

BOO Motivation Approach

Head Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

Future Work

Publications

References

# Control Design Goals

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation  
Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues  
Approach

iDG Results

Future Work

Publications

References

- Stabilize  $z$ , pitch, and roll states, *i.e.*

$$\mathbf{x} = \begin{pmatrix} z \\ \theta \\ \phi \end{pmatrix}$$

- By solving an adaptive state feedback controller, optimal regulation, and minimize parametric uncertainties

# Control Design Goals

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

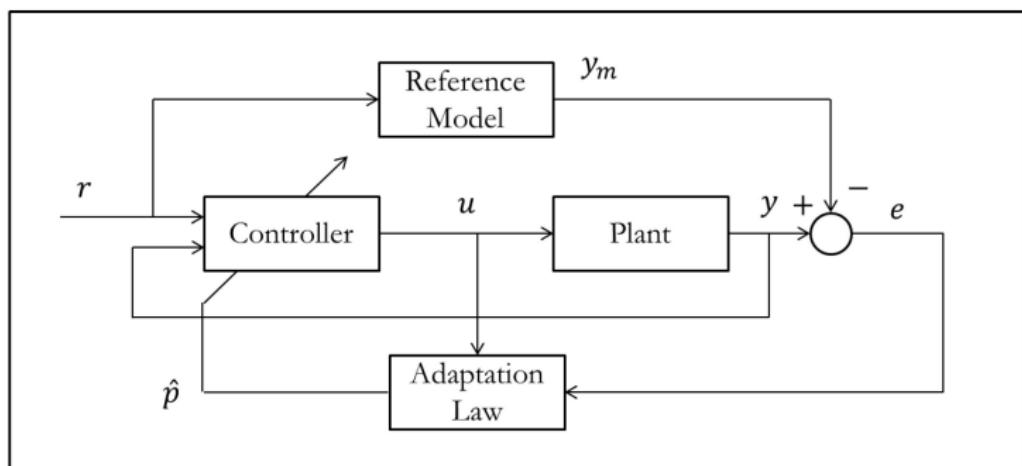
Robustness issues  
Approach  
iDG Results

Future Work

Publications

References

- Provide closed loop tracking given a desired trajectory,  $r$
- Robustify system to (non-)parametric uncertainties



Indirect MRAC system. (Source mdpi.com)

# Model Reference Adaptive Control

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

- Model head and bladder dynamics as
  - $\dot{x} = Ax + B\Lambda(u - f(x, u)) + w(k)$
- Approximate  $f(x, u)$  by a neural network with continuous memory states
- Derive adaptive adjustment mechanism from Lyapunov analysis for Adaptive Control Parks (1966)
  - $u = \underbrace{\hat{K}_x^T x}_{\text{state feedback}} + \underbrace{\hat{K}_r^T r}_{\text{optimal regulator}} + \underbrace{\hat{f}(x, u)}_{\text{approximator}}$

# Neural Network Architecture

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

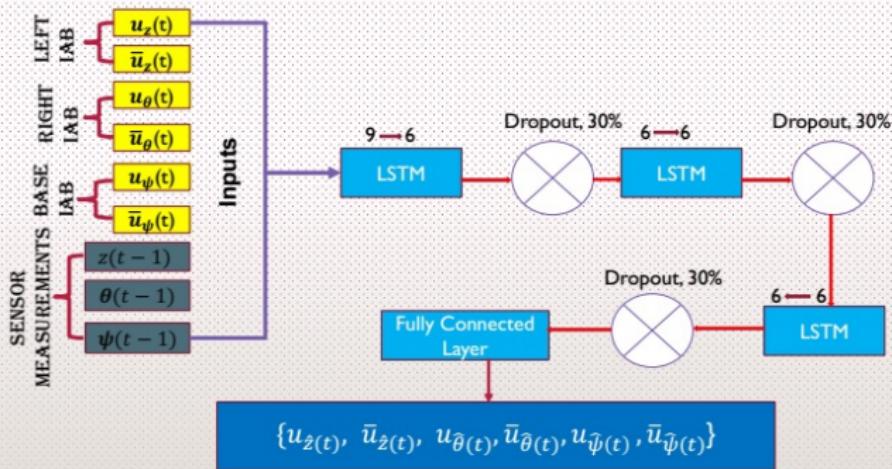
BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

## Neural Net Architecture



# Lyapunov Redesign: Theorem

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

- For correct adaptive gains,  $\hat{\mathbf{K}}_x$  and  $\hat{\mathbf{K}}_r$ ,  $\mathbf{e}(k)$  is ***uniformly ultimately bounded***, and the state  $\mathbf{x}$  converges to a neighborhood of  $\mathbf{r}$ .
- Choose a  $\mathbf{V}$  in terms of  $\mathbf{e}$ ;  $\tilde{\mathbf{K}}_x^T$ ,  $\tilde{\mathbf{K}}_r^T$ ; and parameter error  $\varepsilon_f(\mathbf{x}(k))$  space

$$\mathbf{V}(\mathbf{e}, \tilde{\mathbf{K}}_x, \tilde{\mathbf{K}}_r^T) = \mathbf{e}^T \mathbf{P} \mathbf{e} + \text{tr}(\tilde{\mathbf{K}}_x^T \Gamma_x^{-1} \tilde{\mathbf{K}}_x^T |\Lambda|) + \text{tr}(\tilde{\mathbf{K}}_r^T \Gamma_r^{-1} \tilde{\mathbf{K}}_r^T |\Lambda|)$$

# Stability Results: Ogunmolu et al. (2017)

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach

iDG Results

Future Work

Publications

References

$$\begin{aligned}\dot{\mathbf{V}}(\cdot) &= -\mathbf{e}^T \mathbf{Q} \mathbf{e} - 2\mathbf{e}^T \mathbf{P} \mathbf{B} \boldsymbol{\Lambda} \varepsilon_f \\ &\leq -\lambda_{low} \|\mathbf{e}\|^2 + 2\|\mathbf{e}\| \|\mathbf{P} \mathbf{B}\| \lambda_{high}(\boldsymbol{\Lambda}) \varepsilon_{max}\end{aligned}$$

- $\{\lambda_{low}, \lambda_{high}\} \equiv \min/\max \text{ eigenvalues of } Q \text{ and } \boldsymbol{\Lambda}$ .
- $\dot{\mathbf{V}}(\cdot)$  is thus negative definite outside the compact set:  
$$\chi = \left( \mathbf{e} : \|\mathbf{e}\| \leq \frac{2\|\mathbf{P} \mathbf{B}\| \lambda_{high}(\boldsymbol{\Lambda}) \varepsilon_{max}(\mathbf{y})}{\lambda_{low}(Q)} \right)$$
  - i.e.  $\mathbf{e}$  is uniformly ultimately bounded, or  $\mathbf{y}(t) \rightarrow 0$  as  $t \rightarrow \infty$ .

# Results: Z and Pitch Motions

Automating  
Treatment  
Planning in  
Radiation  
Therapy

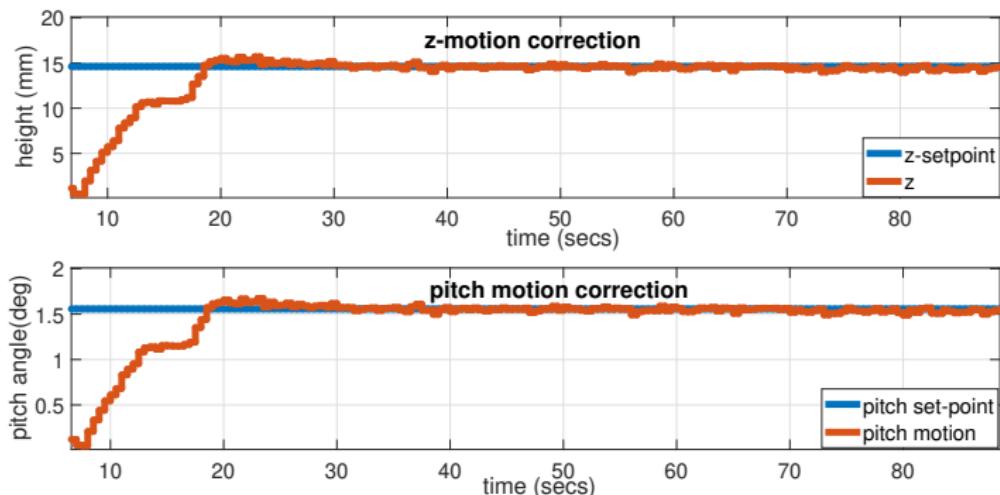
Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



Goal command:  $(z, \theta, \phi) = (14\text{mm}, 1.6^\circ, 45^\circ)^T$ .

# Results: Roll Motion

Automating  
Treatment  
Planning in  
Radiation  
Therapy

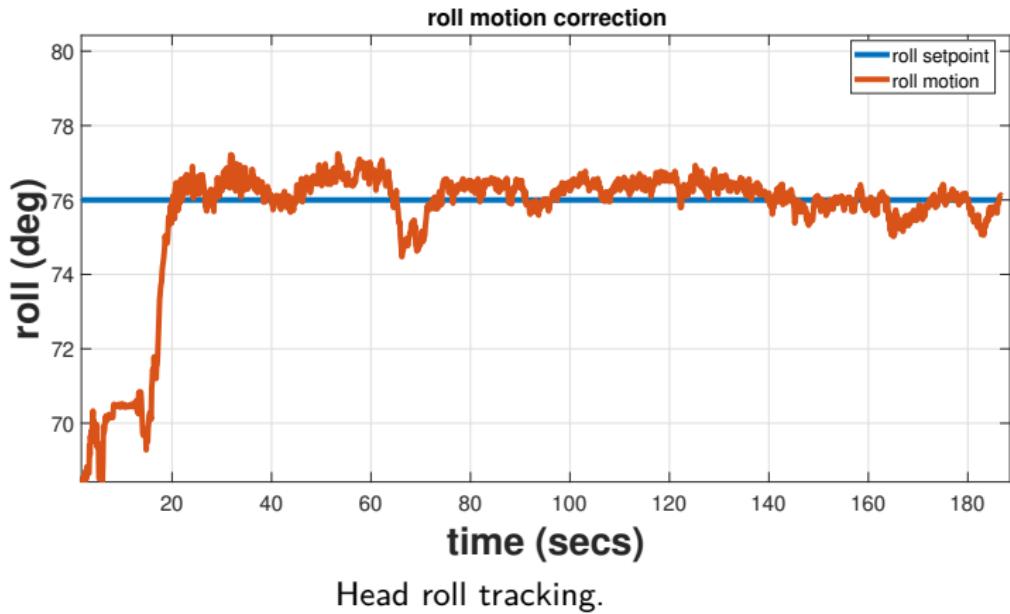
Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References



# Conclusions

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

Future Work

Publications

References

- Non-invasive soft robot for head motion compensation ✓
- Photons-transparent as opposed to rigid/electro-mechanical devices/robots ✓
- Adaptable under MRI coils for newer MRI-LINACs ✓

# Part III: Robustness Margins and Robust Deep Policies

Automating Treatment Planning in Radiation Therapy

Lekan Ogunmolu

BOO

MCTS  
BOO Motivation

Approach

Head Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

Future Work

Publications

References

- Robustness Margins and Robust Deep Policies for Nonlinear Control

# The robustness conundrum

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

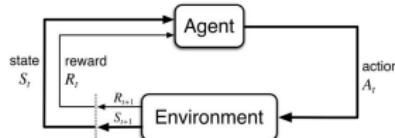
BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

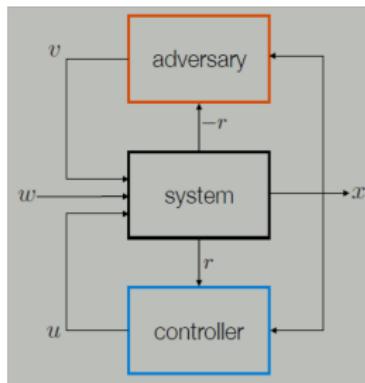
iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

- How to know *a priori* a policy's robustness limits?



- How to inculcate robustness into multistage decision policies?



# Problem Setup

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues

Approach  
iDG Results

Future Work

Publications

References

- To quantify the brittleness, we optimize the stage cost

$$\max_{\mathbf{v}_t \sim \psi \in \Psi} \left[ \sum_{t=0}^T \underbrace{c(\mathbf{x}_t, \mathbf{u}_t)}_{\text{nominal}} - \gamma \underbrace{g(\mathbf{v}_t)}_{\text{adversarial}} \right]$$

- To mitigate lack of robustness, we optimize the *cost-to-go*

$$\mathcal{J}_t(\mathbf{x}_t, \pi, \psi) = \min_{\mathbf{u}_t \sim \pi} \max_{\mathbf{v}_t \sim \psi} \left( \sum_{t=0}^{T-1} \ell_t(\mathbf{x}_t, \mathbf{u}_t, \mathbf{v}_t) + L_T(\mathbf{x}_T) \right),$$

- and seek a saddle point equilibrium policy that satisfies

$$\mathcal{J}_t(\mathbf{x}_t, \pi^*, \psi) \leq \mathcal{J}_t(\mathbf{x}_t, \pi^*, \psi^*) \leq \mathcal{J}_t(\mathbf{x}_t, \pi, \psi^*),$$

# Results: Brittleness Quantification

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation

Approach

Head  
Stabilization  
IMRT

MRI-LINAC

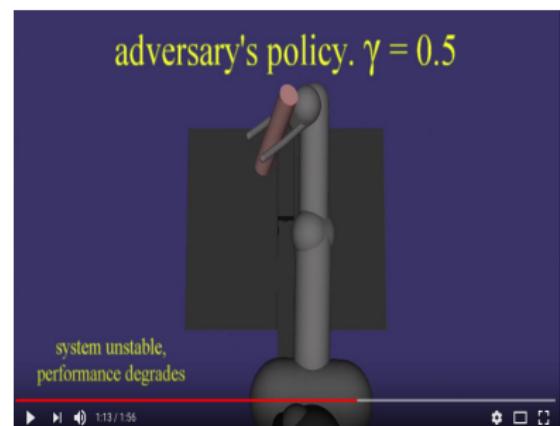
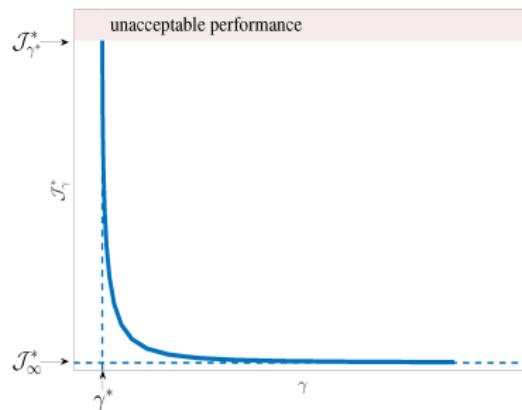
iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References



# Results: Iterative Dynamic Game

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation

Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues

Approach

iDG Results

Future Work

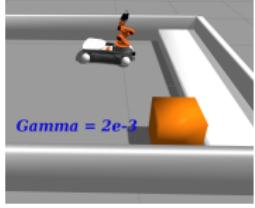
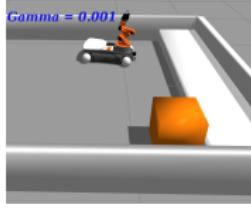
Publications

References

$y_1^*$



$y_2^*$



End pose of the KUKA platform with our iDG formulation given different goal states and  $\gamma$ -values

# Future Work: MRI/RT Immobilization

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO  
MCTS  
BOO Motivation  
Approach

Head  
Stabilization  
IMRT  
MRI-LINAC

iDG  
Robustness issues  
Approach  
iDG Results

Future Work  
Publications  
References

- Explore multiple parallel robot mechanisms for head motion correction.
- Adopt iterative dynamic game approach [Ogunmolu et al. (2018)] for solving robust controller for head stabilization.
- Build on Freeman and Kokotovic's point-wise min-norm robust control lyapunov function to realize a meaningful value function in deep policies [Freeman and Kokotovic (1996)].

# Conclusions

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References

- Designed a non-invasive soft robot for head motion compensation in IMRT/emerging MRI-LINACs ✓
- Photons-transparent; Adaptable under MRI coils for newer MRI-LINACs ✓
- Fast inference of beam orientations in treatment planning:  
Approx 60 secs beams prediction time✓
- Adapted  $H_{\infty}$  control methods for quantifying the brittleness of deep policies✓
- Devised a min-max-trained deep saddle policy for mitigating model mismatch, transfer errors, and policy sensitivity e.t.c. ✓

# Publications

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References

- **Ogunmolu, Olalekan**, Xinmin Liu, Nicholas Gans, and Rodney D. Wiersma. "Mechanism and Model of a Soft Robot for Head Stabilization in Cancer Radiation Therapy." In *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 4609-4615. IEEE, 2020.
- **Ogunmolu, Olalekan**, and Rodney D. Wiersma. "Kinematics and Kinetics of a Continuum Parallel Soft Robot for MRI-LINAC Motion Correction." Working Paper, In *IEEE Transactions on Robotics*, IEEE 2020.
- **Ogunmolu, Olalekan** and Rodney D. Wiersma. "A Real-Time Patient Head Motion Correction Mechanism for MRI-Linac Systems." In *2020 Virtual Joint AAPM/COMP Meeting*, AAPM 2020.
- **Ogunmolu, Olalekan**, Xinmin Liu, Rodney D. Wiersma. "Auto-Determination of the Dextrous WorkSpace in Robotic Stereotactic Radiosurgery." In *2020 Virtual Joint AAPM/COMP Meeting*, AAPM 2020.
- **Ogunmolu, Olalekan**, Nicholas Gans, and Tyler Summers. "Minimax iterative dynamic game: Application to nonlinear robot control tasks." In *2018 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 6919-6925. IEEE, 2018.
- **Ogunmolu, Olalekan**, Nicholas Gans, and Tyler Summers. "Robust zero-sum deep reinforcement learning." *arXiv preprint arXiv:1710.00491* (2017).
- Summers, Tyler, **Ogunmolu, Olalekan**, Nicholas Gans. "Robustness Margins and Robust Guided Policy Search for Deep Reinforcement Learning." In *IEEE/RSJ International Conference on Robots and Intelligent Systems,(Abstract Only Track)*, vol. 8. 2017.

# Publications

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS  
BOO Motivation  
Approach

Head  
Stabilization

IMRT  
MRI-LINAC

iDG

Robustness issues  
Approach  
iDG Results

Future Work

Publications

References

- **Ogunmolu, Olalekan**, Gans, Nicholas, Jiang, Steve, and Gu, Xuejun. "SU-E-J-12: An Image-Guided Soft Robotic Patient Positioning System for Maskless Head-And-Neck Cancer Radiotherapy: A Proof-Of-Concept Study." *Medical Physics* 42, no. 6Part7 (2015): 3266-3266.
- **Ogunmolu, Olalekan P.**, Xuejun Gu, Steve Jiang, and Nicholas R. Gans. "A real-time, soft robotic patient positioning system for maskless head-and-neck cancer radiotherapy: an initial investigation." In *2015 IEEE International Conference on Automation Science and Engineering (CASE)*, pp. 1539-1545. IEEE, 2015.
- **Ogunmolu, Olalekan P.**, Xuejun Gu, Steve Jiang, and Nicholas R. Gans. "Vision-based control of a soft robot for maskless head and neck cancer radiotherapy," In *2016 IEEE International Conference on Automation Science and Engineering (CASE)*, pp. 180-187.IEEE, 2016.
- **Ogunmolu, Olalekan**, Adwait Kulkarni, Yonas Tadesse, Xuejun Gu, Steve Jiang, and Nicholas Gans. "Soft-neuroadapt: A 3-dof neuro-adaptive patient pose correction system for frameless and maskless cancer radiotherapy." In *2017 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 3661-3668. IEEE, 2017.
- Almubarak, Yara, Joshi, Aniket, **Ogunmolu, Olalekan**, Gu, Xuejun, Jiang, Steve, Gans, Nicholas, and Tadesse, Yonas. "Design and development of soft robot for head and neck cancer radiotherapy." In *Electroactive Polymer Actuators and Devices (EAPAD) XX*, vol. 10594, p. 1059418. International Society for Optics and Photonics, 2018.

# Publications

Automating  
Treatment  
Planning in  
Radiation  
Therapy

Lekan  
Ogunmolu

BOO

MCTS

BOO Motivation  
Approach

Head  
Stabilization

IMRT

MRI-LINAC

iDG

Robustness issues  
Approach

iDG Results

Future Work  
Publications

References

- Johannes Heinrich, Marc Lanctot, and David Silver. Fictitious self-play in extensive-form games. In *International Conference on Machine Learning*, pages 805–813, 2015.
- Sadeghnejad Barkousaraie, Azar and Ogunmolu, Olalekan and Jiang, Steve and Nguyen, Dan. A Fast Deep Learning Approach for Beam Orientation Selection Using Supervised Learning with Column Generation on IMRT Prostate Cancer Patients. *Medical Physics, American Association of Physicists in Medicine*, 2019.
- Radhini Chelvarajah, Brigid Leighton, Linda Martin, Wayne Smith, and Rachael Beldham-Collins. Cranial immobilisation—is there a better way? *Radiographer*, 51(1):29–33, 2004.
- Xinmin Liu, Andrew H Belcher, Zachary Grelewicz, and Rodney D Wiersma. Robotic stage for head motion correction in stereotactic radiosurgery. In *2015 American Control Conference (ACC)*, pages 5776–5781. IEEE, 2015.
- Andrew Belcher. *Patient Motion Management with 6-DOF Robotics for Frameless and Maskless Stereotactic Radiosurgery*. PhD thesis, The University of Chicago, 2017.
- Olalekan Ogunmolu and Rodney Wiersma. A Real-Time Patient Head Motion Correction Mechanism for MRI-Linac Systems. In *Joint AAPM / COMP Meeting, Virtual*, 2020.
- James Pikul, Itai Cohen, and Robert Shepherd. Stretchable surfaces with programmable texture, May 2 2019. US Patent App. 16/161,029.
- PC Parks. Liapunov Redesign of Model Reference Adaptive Control Systems. *IEEE Transactions on Automatic Control*, 11(3):362–367, 1966.
- Olalekan Ogunmolu, Adwait Kulkarni, Yonas Tadesse, Xuejun Gu, Steve Jiang, and Nicholas Gans. Soft-NeuroAdapt: A 3-DOF Neuro-Adaptive Patient Pose Correction System for Frameless and Maskless Cancer Radiotherapy. In *IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS), Vancouver, BC, CA*, pages 3661–3668. IEEE, 2017.
- Olalekan Ogunmolu, Nicholas Gans, and Tyler Summers. Minimax Iterative Dynamic Game : Application to Nonlinear Robot Control. *IEEE International Conference on Intelligent Robots and Systems*, 2018.
- Randy A Freeman and Petar V Kokotovic. Inverse optimality in robust stabilization. *SIAM journal on control and optimization*, 34(4):1365–1391, 1996.