Learning, Optimization & Design for Healthcare Systems

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I. Introduction

We are interested in fundamental decision and design problems in human-machine collaboration and skill-augmentation, with a focus on healthcare. Inference and optimization in healthcare are often hard multi-stage stochastic models, but we explore efficient reformulations and heuristics with guarantees. Specifically, we have studied algorithmically grounded solutions for integration of autonomy in internal radiotherapy for cancer and subtask automation in Robot-assisted minimally invasive surgery (RMIS).

Currently, RMIS devices are controlled by surgeons in a local tele-operation mode. Procedures often last multiple hours and highly depend on surgeon skill. Autonomy of surgical subtasks has the potential to assist surgeons, reduce fatigue, and facilitate supervised autonomy for tele-surgery. Although, LfD has been shown to be useful for learning control policies for various primitive actions [1], surgical domain has its challenges such as specular workspace and constrained dexterity. We consider learning task representations as "milestones" from demonstrations and use multimodal sensory input for classification of success criterion.

High Dose Rate Brachytherapy (HDR-BT) is an internal radiation therapy and is prevalent for cancer treatment in many body sites such as mouth, breast and prostate. It involves radioactive sources placed temporarily proximal to or within tumors. Current methods for intracavitary and interstitial HDR-BT use generic templates which result in inadequate dose coverage and healthy organ puncture, respectively. We present novel patient specific 3D-printed implants and needle guides for respective modes; we also evaluate robot-assisted needle implants for interstitial HDR-BT. Further, we pose the treatment planning for problem as a discrete conic optimization to achieve optimality guarantees.

II. Learning & Automation in Surgical Subtasks

Robot-assisted minimally invasive surgery (RMIS) has ushered in an era of shorter recuperation time, lower patient trauma, shorter hospital stay and lesser tissue injury. Regardless of the benefits, MIS requires skilled surgeons to perform tediously long procedures with reduced sensory perception during surgical manipulation.

We are working towards surgical sub-task automation and explored a 'Learning By Observation' approach for autonomously manipulating deformable viscoelastic tissue and pattern cutting in 2D orthotropic gauze [2]. Herein, we identify, segment, and parameterize sub-trajectories ('surgemes') and sensor conditions to build a finite state machine (FSM) for each subtask. The robot then executes the FSM repeatedly to tune parameters and if necessary update the FSM structure.

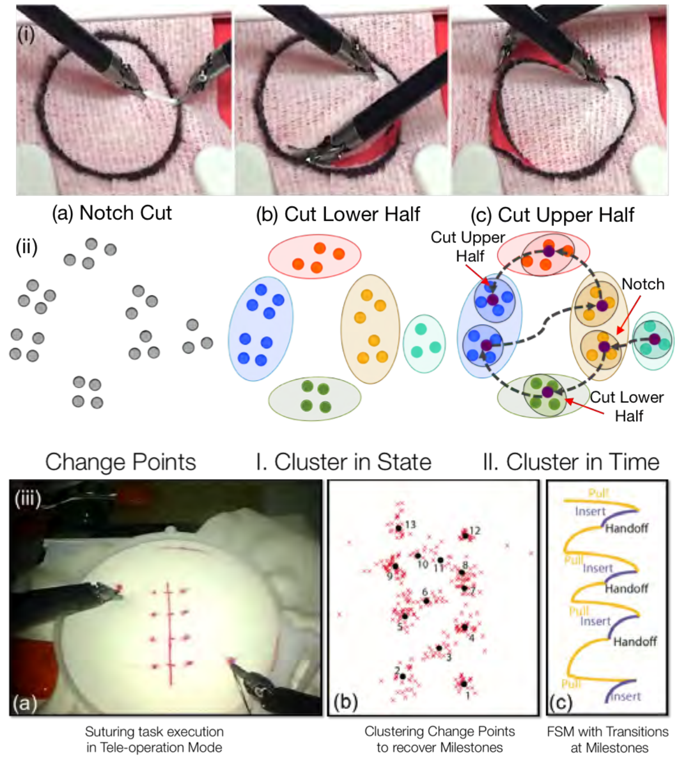

Fig. 1: Row (i) depicts the pattern cutting task. Row (ii) illustrates the corresponding 'change points', which are clustered in space and time to achieve temporally ordered 'milestones'. The FSM with transitions at milestone for the pattern cutting task is similar to the manually designed FSM in [2]. Row (iii) shows a suturing task that involves passing a needle through 4 pairs of holes and the recovered milestones from data qualitatively match a semantic segmentation.

While these results are promising, automating these subtasks requires manual effort in tuning the FSM that integrates robot actions and perception. We are currently exploring a data driven approach for reduction in training effort with unsupervised structure learning by identification of state 'milestone' from task demonstrations and imputing sensory classifiers as success criterion for each 'milestone' as shown in Figure 1. We pose this as a non-differentiability condition in each trajectory of state/sensor space to get 'change points'. We then cluster similar change points across all demonstrations into what we call 'milestones'. These milestones encode two important aspects: (pre-condition) the state of the robot prior when reaching the milestone and (post-condition) the state of the environment when completing a milestone. This gives a notion of necessary conditions for task success, where a robot has to ensure that it satisfies the post-condition before proceeding.

Lack of tactile feedback in RMIS also limits autonomous operation. We have designed a novel low-cost palpation probe

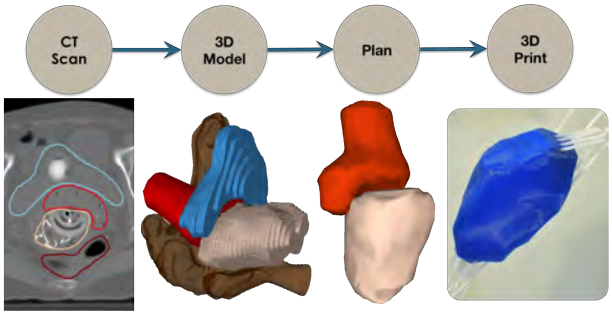

Fig. 2: The sequence of figures depicts the proposed procedure for creating a custom implant. A CT-Scan is used to generate 3D models; which are smoothed to get mesh models, and used for treatment planning and internal channel planning in cavity. Thereafter, a cavity conformal implant is created using 3D printing as shown

for RMIS to localize subcutaneous blood vessels [3]. It measures probe tip deflection using a Hall Effect sensor as the tip is moved across a surface. Initial evaluation with automated quasi-static sliding-mode on silicone based tissue phantoms with cylindrical subcutaneous blood vessel phantoms show that the probe can detect phantoms of diameter 2.25 mm at a depth of up to 5 mm below the tissue surface.

III. Brachytherapy: Planning and Delivery

Internal form of radiotherapy for cancer treatment, known as Brachytherapy, involves radioactive source placement in proximity to or within the tumor; and it is used for over $500,000$ patients annually in the US. A major challenge here is to accurately place sources on a set of planned dwell positions to sufficiently irradiate the tumors while limiting radiation damage to healthy organs and tissues. We focus on improving autonomy by addressing problems in optimal dose distribution planning and novel techniques of accurate source placement for dose delivery. We study research challenges in (a) Algorithmically designed customized 3D printed bio-compatible implants for Intracavitary Brachytherapy with demonstrated use case in oral-nasopharynx and lower-canal gynecological tumors [4] and (b) Robot-assisted implant for Interstitial Brachytherapy for deep seated prostate tumors [5].

Intracavitary Brachytherapy: It is used for tumors near body cavities (≤ 1 cm of the surface) and it avoids tissue puncture during source placement. Current methods use one-size-fits-all standard applicators that are prone to shifting inside the cavity, resulting in suboptimal dose. We propose a new approach in [4] that leverages 3D printing and steerable needle motion planning ([6]) to create patient specific implants containing curvature-constrained internal channels, that fit securely, minimize air gaps, and precisely guide radioactive sources to the target through 3D printed internal channels (Figure 2). 3D printing allows us to customize the external shape of the applicator to fit the cavity contours, and also build internal channels. The treatment planning problem here is a version of sensor placement problem with a monotone submodular additive coverage function instead of the discrete coverage function. We model it as a mixed integer conic problem allowing continuous positions for sources inside cavity.

Interstitial Brachytherapy: It involves tissue puncture for placing sources in the tumors such as in prostate. It constraints the dwell positions to be inside a set of straight line catheters, and a lower number of catheters is desired to minimize tissue damage through puncture. The key challenges here are guaranteed radiation coverage to tumor and accurate source placement. Currently used rigid templates require that all needles be parallel, whereas skew-line configurations can avoid puncturing healthy organs and maintain clinically acceptable doses. We proposed the use of a robot [5] and custom needle guides [7] for prostate brachytherapy achieving clinical doses with placement accuracy at par with an expert (Figure 3).

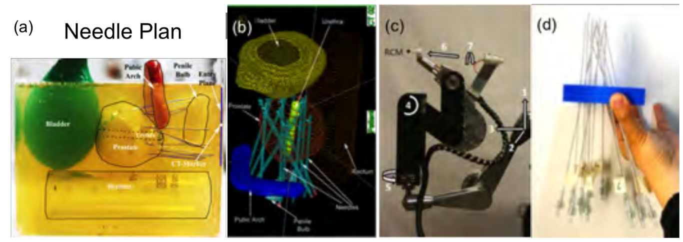

Fig. 3: Illustration of a prostate phantom (a) along with a needle plan (b). Two methods of needle configuration implant are shown in: (c) Robot-Assisted [5], and (d) 3D printed needle guide [7].

IV. Impact and Future Work

We are excited to continue research in the integration of information optimization and design of physical systems, with a focus on practical applications in healthcare and surgery. Our overarching goal is to build algorithmically grounded, actor-agnostic, low-cost solutions for these applications.

Initial results in representation learning of surgical subtasks motivate study of extensions such as: (a) Use of only sensor data for task representation as milestones, (b) Unsupervised success classifiers in sensor space (c) Building a grammar of surgical "dexemes". Our work in customized implants also introduces altogether new mode of intracavitary treatment, with new problems such as dose planning guarantees and inclusion of radiation shielding material in planning and design.

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