Autonomy in Robotic Surgery: the First Baby Steps

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INTRODUCTION

Two classifications of autonomy have been proposed for the fields of self driving cars, and surgical robots organized in six levels:

0	No Autonomy/Automation during the task
1	Assistance to the operator during the task
2	Partial automation on executing single acts
3	Supervised plan/execution of act sequences
4	Unsupervised plan/execution of a full task
5	Plan/execution of full task

The most important technologies for the complete autonomy stack must be developed to reach the first two levels, since they will provide surgeons with guidance, support and simple autonomous tasks. Here, we present our efforts to develop these basic technologies.

MATERIALS AND METHODS

The quest of a cognitive architecture has produces good results, e.g. the I-SUR (Intelligent Surgical Robot) framework, but the integration of *a priori* knowledge with experimental data is still an open question. Here, we represent *a-priori* knowledge with an ontology and robot motions with a *Finite State Machine* (FSM*)* in the context of a peg-and-ring task, which is a standard training exercise for robotic surgery.
The FSM models the peg-and-ring actions learned from experimental data and the Ontology encodes the semantic knowledge about the task and can be used for planning and reasoning. The overall framework is implemented in Robot Operating System (ROS).
Motion actions are learned using the Dynamic Movement Primitives (*DMPs*) approach that generates a point-to-point trajectory by solving the following second order Ordinary Differential Equation (ODE) of spring-mass-damp type. We employ this method because the trajectory can be learned from a single instance of a motion and can be generalized to multiple instances.
To account for the highly deformable anatomic tissues we are developing realistic models using finite element methods (*FEM*) to compute the tissue positions by solving physical balance laws, but also evaluating the use of geometry-based approaches, e.g position-based dynamics (*PBD*), to model objects as an ensemble of particles. Because of the deformable environment, standard localization methods, e.g. Simultaneous Localization and Mapping (SLAM) cannot be applied directly to command instrument motions, landmark tracking must replace identification to localize the instruments.
We are also analyzing real clinical data to extract task structure, by integrating Deep Learning techniques with a-priori knowledge, e.g. ontologies, to reduce training time and dependency on data set annotation.

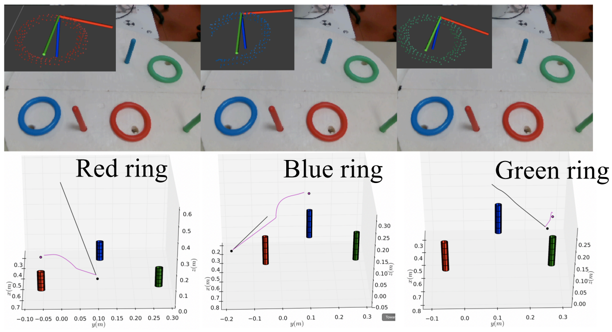

Fig. 1: End effector trajectories grasp and obstacle avoidance in different settings.

RESULTS

Figure 1, shows an example of the peg-and-ring task using the proposed cognitive architecture. The actions of peg reaching, grasping and moving to destination are learned by generalizing the DMP execution of three separate actions, one per color. The position of the rings on the table are randomly set and the DMP module adapt the trajectory parameters to the current ring and peg locations. The pre- and post-conditions of each action are verified by the ontology module, that also checks the validity of the sensory data. Motions are learned without the presence of obstacles and at run time they are automatically adapted to the environment.

DISCUSSION

As the first step towards an autonomous surgical robot, we define a hybrid cognitive architecture where rules represent the discrete (or logical) state of the task while motion control, i.e. the continuous, time-driven, part of the task, are implemented using the DMP paradigm. Motions can be abstracted and adapted to different anatomical situation, without changing the logical task structure. Thus the robot can learn a motion, represent it with an abstract concept, e.g. a suture, and adapt it to a specific case, all within the ontology and DMP hybrid anatomy.

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