Modeling and Validation of a Low-Cost Soft-Tethered Endoscopic Platform

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INTRODUCTION

Nearly 70% of gastric and esophageal cancer cases occur in Low- and middle-income countries (LMICs) and account for 10% of the incident cases worldwide [1]. Screening programs have been shown to be effective in reducing the mortality rate through early detection; however, the resource intensive nature of these programs limits their widespread implementation [2]. In an attempt to overcome these issues, the HydroJet is being developed as a low-cost ($2 to $5 per procedure) endoscopic platform (Fig. 1). The platform was firstly introduced in [3]. The objective of the HydroJet is to serve as a primary screening modality. The system was designed to be portable and disposable—obviating the need for specialized reprocessing/cleaning so that it can be taken to rural and remote locations in LMICs where access to healthcare may not be available. As a primary screening modality, if a suspicious lesion is found, the patient can be triaged to a healthcare institution for further investigation/therapy.

The HydroJet platform consists of a disposable flexible tether with an attached capsule containing a camera for stomach visualization. Actuation of the system is performed using three water jets built into the capsule. Each of the jets can be controlled separately to aim the camera at screening landmarks within the stomach. The tether of the platform has been upgraded with respect to [3] to achieve a lower bending stiffness and a more symmetric workspace. It consists of three Tygon tubes held together using rubber O-rings at regular intervals.

The objective of this study is to investigate kinematic modeling of the HydroJet tether—as an accurate model of its behavior can (a) be utilized for closed loop system control and (b) predict tether behavior for optimization of platform design. As the primary goal of the platform is to orient the camera within the workspace of a human stomach, an error of up to 10 mm is acceptable.

MATERIALS AND METHODS

A. Modeling

The forward kinematics are obtained using a rigid link model, as it is both computationally efficient and capable of modeling manipulators with non-constant curvature [4]. The manipulator is modeled as a chain of n interconnected rigid links with $n+1$ stiff joints connecting each link. The model combines the forward kinematics described by [5] (Fig. 2, top) and the statics described by [4] (Fig. 2, bottom).

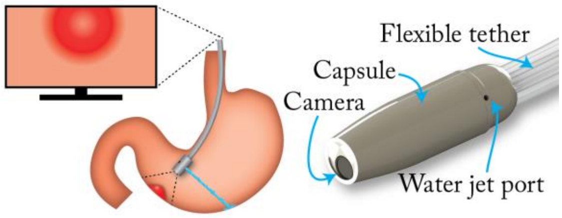

Fig. 1 Left: the HydroJet platform while visualizing part of the stomach. Right: a close-up of the capsule.

In contrast to [4, 5], this model does not assume constant length for each rigid link. This approach enables modeling of manipulators tracked with position or orientation sensors placed at arbitrary locations and enables selective refinement of the model for parts of the manipulator with large curvature. Additionally, the bending stiffness of each joint can be set separately in order to account for stiffer parts of the manipulator, like the HydroJet capsule. Following the derivation in [4], the stiffness of the joints is given by:

$$k_i = \begin{cases} \left(\frac{l_i}{2E_iI_i} + \frac{l_{i+1}}{2E_{i-1}I_{i-1}}\right)^{-1} & i \neq 1, n+1 \\ 2E_1I_1/l_1 & i = 1 \\ 2E_nI_n/l_n & i = n+1 \end{cases} \quad (1)$$

where k_i is the stiffness of joint i, E_iI_i is the bending stiffness of link i, and l_i is the link length.

Actuation of the HydroJet is modeled as a force acting on the tip of the rigid link model. The jet force for each possible valve opening is measured beforehand. The gravity acting on the HydroJet is considered to be uniformly distributed along its length. Lastly, the bending stiffness of the capsule has been included in the model to take the rigid tip into account.

B. Calibration and validation

A calibration procedure is performed to determine both the tether bending stiffness and the jet orientation, as these parameters are initially unknown. During calibration, inputs for three independent sweeps (Fig. 3) –one for each jet–are fed to the system and the resulting static equilibrium tip positions are measured for a tether length of 58 mm. Each sweep is split into 31 steps. Next, these measurements are compared to model estimations for the same inputs and the minimum least squares error method is used to find the bending stiffness and jet angle that minimize the error in tip position and orientation.

During validation, the inputs for three independent sweeps and three paths were fed to the system. This time sweeps were performed at a tether length of 58 mm (31

steps), one path was performed at 58 mm (25 steps) and the other two paths were performed at 68 mm (25 and 31 steps). The accuracy of the calibrated model was determined by comparing the validation set, containing tip position and orientation, to the model estimations.
For both calibration and validation, the Aurora electromagnetic tracking system (Northern Digital, Inc.) was utilized to track deflection with two 6-dof sensors, placed at the base of the tether and inside of the capsule.

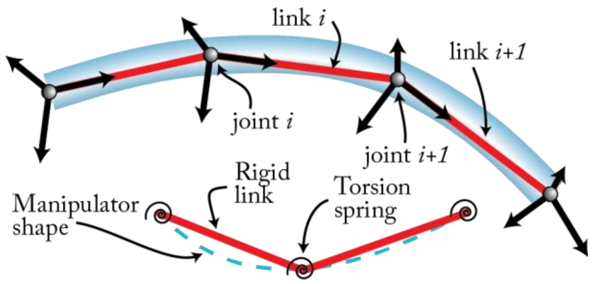

Fig. 2 The manipulator modeled as a chain of interconnected rigid links (top). Each rigid link approximates a constant curvature arc and manipulator stiffness is modeled using torsion springs at the joints (bottom).

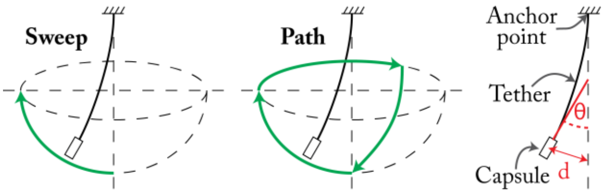

Fig. 3 The HydroJet can perform a sweep (one jet) or track a path (multiple jets). For a 68 mm long tether, the maximum capsule displacement d is 65 mm during a sweep.

RESULTS

The results for all experiments are summarized in Table 1. A visual comparison between the estimated and measured positions of three sweeps is shown in Fig. 4. The results show that each position and orientation can be estimated with a relative error of 17.6% (SD: 14.1%) and 13.5% (SD: 9.3%) respectively. The errors for the sweeps are lower than the errors for the paths.

Tab. 1 The results of the validation. The absolute errors are determined by directly comparing the measurements and estimations. The relative errors take the deviation from the reference configuration into account.

	Error type	Sweep	Path	Total
Position	Mean abs. error [mm]	6.0	8.1	6.9
	SD of abs. error [mm]	4.8	6.3	5.7
	Mean rel. error [%]	14.4	20.6	17.6
	SD of rel. error [%]	6.1	18.3	14.1
Orientation	Mean abs. error [°]	3.7	5.7	4.6
	SD of abs. error [°]	2.1	4.0	3.3
	Mean rel. error [%]	10.1	16.6	13.5
	SD of rel. error [%]	4.4	11.4	9.3

DISCUSSION

This study describes and validates kinematic modeling of the HydroJet platform. These initial results demonstrate that the presented model is accurate for estimating both tip position and orientation. Additionally, estimation of tip behavior is more accurate for sweeps than for paths.

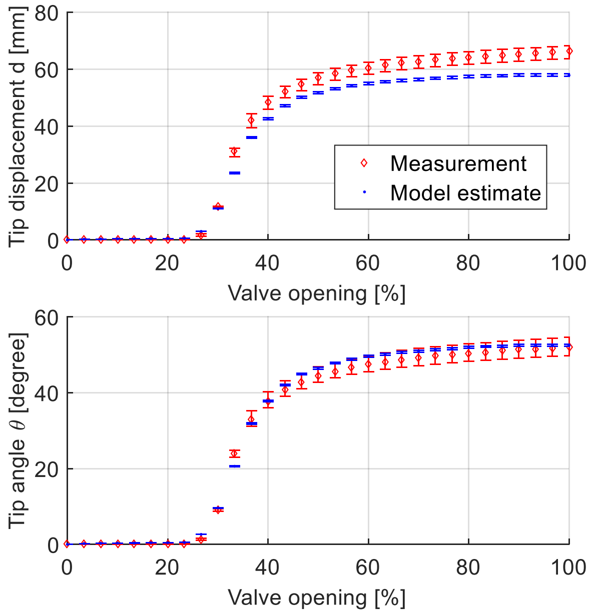

Fig. 4 Measured and estimated tip position and orientation for three separate sweeps. The error bars indicate the ranges for the three sweeps.

The work described in this paper combines two available models and expands them by including variable link lengths and variable manipulator stiffness. The resulting model can also be applied to other areas, e.g. for catheters with variable bending stiffness along their length.
The HydroJet platform is currently under open-loop control. By implementing the model described above, it might be possible to implement closed-loop control that would vastly enhance system usability/intuitive use.
In this study, the position of the base of the tether was known; however, in the clinical setting, this may not be the case. Therefore, research investigating online estimation of tether length and base position is underway.

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