An intelligent data fusion system concept for the STIFF-FLOP project

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*Abstract***— This paper describes the design of an experimental setup of flexible modular medical manipulator, equipped with optic-fiber sensors, developed in Stiff-Flop project for Minimal Invasive Surgery purposes. The setup is being used to validate and verify the implementation of a model used for position estimation and applied data fusion approach. Flexible manipulators are emerging technology in medical applications especially in minimally invasive surgery as it allows to perform the operation with tight space constraints without damaging other organs. The paper discusses the technical challenges in implementation of data fusion for estimation of the position of the flexible manipulator during surgery. Both the experimental setup and the data fusion system are presented and described in the paper. The result of the work are presented in form of a test stand that is demonstration capable.**

I. Introduction

Minimal invasive surgery (MIS) that is performed by the surgeon through small incisions is an established alternative to conventional open surgery [1]. Main advantages are reduced post-operative pain, blood loss, tissue trauma and recovery time. Additional benefit is lower probability of post-operative infection [2]. However, there are also some limitations connected to the use of that technique. The surgeon has limited feedback and there is also a reduced number of degrees of freedom available to the surgeon during the operation. Research conducted in projects like Stiff Flop (EU FP7 founded project) is focused on introducing new flexible robotic manipulators into the MIS. This kind of structures are able to bend in a snake-like way and thanks to that the number of degrees of freedom is increased during MIS [7]. Majority of the mentioned problems can be reduced or eliminated. Another challenge of using such structure for MIS is the accuracy that is required to perform the operation. Currently there is no one good solution to estimate the localization of the manipulator in a surgery scene. To provide accurate and reliable positioning and control of the flexible structure multiple position estimation sources are required [6] which is connected to development of both – sensors [4] and data fusion system. This paper presents the experimental setup of soft manipulator structure with multiple sensing modalities and data processing system. The design of the STIFF-FLOP soft robot module is presented on Fig. 1. Each module is built with a braided silicone rubber tube of 2.5cm in diameter. Inside the tube, there are three pressure chambers [7]. The air or fluid pressure within each of these three chambers determine the bending, elongation and direction in 3D space. This design is inspired from a three-chamber micro actuator first proposed by Suzumori [8].

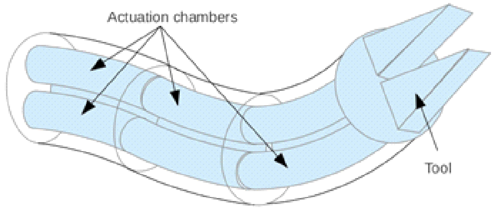

Fig. 1: Stiff-Flop robot module visualization

II. Complexity of the Task

Major complications that need to be considered when modeling the robot behavior result from changes in geometry of the manipulator actuation chambers. Whenever the pressure is applied to the actuation chamber, its elongation and cross-section diameter increase. As chamber elongation is desired and fully addressed by the model, the change in chamber cross section is a source of error. As each module of the manipulator is externally braided in order to prevent major deformation, the actuation chamber inside the module will display an increase in cross-section radius along with displacement of cross-section center when the pressure is applied. This will result in displacement of manipulators 'spine', while the model assumes that the spine is located in the very center of module cross-section and the centers of actuation chambers are placed on the same constant radius.

Another issue that needs to be considered is related to dynamics of pressure application to certain actuation chambers. The resulting cross-section geometry of manipulator module strongly depends on the sequence of pressure application, because the chambers will adapt their shape to actual constraints within the module volume. For example, consider the case when the same pressure is applied simultaneously inside two actuation chambers. The resulting cross-section geometry will be different from a case when these chambers are pumped sequentially with the same pressure. At the outcome of both cases there are two chambers with the same pressures, however the cross section geometries vary. This also causes the manipulator position to be different than predicted by the models. The authors have a hypothesis about what is the cause of such behavior. When inflating one actuation chamber, its expansion causes the other chamber to stick to the external braiding. Because of the friction between silicon and the braiding, the second chamber has to exert more force that the inflated one, which may be the cause of observed asymmetry.

The complications described above clearly show that calculating manipulators position based on only one mathematical model is insufficient. A mathematical model which would take into account all above and In order to achieve reasonable precision and relevance, the implementation of data fusion combining mathematical model and readings from manipulator sensors is critical in terms of projects application.

III. Available sensor systems

The medical application of the Stiff-Flop system imposes strict safety requirements. Any medical equipment has to exhibit high reliability. This is achieved by the use of a multi-redundant sensor system. The restriction to non-metal materials only forces the use of a novel set of sensors and new adequate data fusion algorithms and concepts. Since any direct tracking systems cannot be used in order to measure the manipulators position, it has to be evaluated with indirect calculation methods using many different sources of information. One method of estimating the robot position is the constant curvature model [11]**,** which is based on the pressure chambers' lengths. In the Stiff-Flop project, those are measured by custom optic fiber sensors. The constant curvature model assumes that no external forces act on the manipulator. Therefore, in order to evaluate the error of the model, the values and directions of the external forces have to be known. At the current state of the project, bending moments between two manipulator segments are measured using custom optical fiber bending moment sensors. More information about those optical sensors can be found in [4] and [12]. Another method that can be used for position estimation of the Stiff-Flop arm is the bending model created by the authors, which will be described in the next paragraph. This model is based on the bending theory and requires the pressure values in each pressure chamber and the moments and forces acting on the manipulator. The pressure data is measured in the control system for regulation and is available to the data fusion software. The last source of information that can be used to calculate the position of the robot is the camera vision system. Because of the tight-spaced nature of the robot's workspace, only the part of the manipulator will be visible at any time. After proper image processing and data extraction, information about the localization of this part of the robot can be estimated.

IV. Bending model

Continuous manipulators pose several additional challenges to analysis and modeling. Because of their increased flexibility, their shapes tend to be more complex, thus, being more difficult to describe in mathematic terms. As it was mentioned earlier, the Stiff-Flop robot consists of segments which are driven by pumping the work fluid in or out of the pressure chambers. In the condition where no external forces act on the manipulator, the segments bend in a circular arc shape. This behavior is described by the Constant Curvature Model [11]. Since the Stiff-Flop arm is designed to operate in tight spaces, there is high probability of contact with other bodies. This fact makes calculating the influence of external forces acting on the arm a must. This significant factor is not considered by the Constant Curvature model, what renders it unusable in this case. Therefore, a new analytical model was required for estimating the robots shape. Such model has been created by the authors and is presented in this paragraph. This model is referenced throughout the text by the name „Bending Model”.

The developed Bending Model is based on Euler-Bernoulli bending theory. For this model, following assumptions had been made: the pressures in each chamber and the values of external forces acting on the module are measured at any point of the module; the segment is made of homogenous material of known stiffness, with three pressure chambers hollowed out; the dimensions of cross-section of the pressure chambers are constant (provided by the braiding); the pressure in chambers is constant at any point. The other influence of the braiding and optical fibers running through the module had been neglected. Nevertheless, the influence of the omitted factors on the model is still subject of the research.

The shape is calculated iteratively in fixed set of points along the manipulator's „spine”. The bend caused by the moments created by the chamber pressures and external forces is calculated at each point and defines the starting position of the next point. The model has been implemented in order to use in the Stiff-Flop system. For more convenient development, MATLAB had been used. Fig. 2 presents a visualization of the calculated manipulator shape in different conditions (pressures and forces acting on the manipulator).

Fig. 2: Visualization of the manipulator shape calculated with Bending Model for different pressures and force values.

V. Data fusion system concept

The Stiff-Flop robot manipulator is designed to navigate efficiently through the tight spaces of the human abdomen. Algorithms that enable carrying out above-mentioned task in an automated way are being developed in the consortium. Most of this algorithms base on the knowledge of the robots current shape. This fact makes efficient and precise data fusion system of significant importance to the overall robot performance. The current state of the system and its key concepts are outlined in this paragraph.

At the time of writing this paper, the authors were not in possession of the custom optical tip force sensor planned to be used in the project. Therefore, for testing the data fusion algorithms a substitute had been found. The forces acting on the tip of the upper segment can be approximated using a constant curvature assumption. First, the robots tip position is calculated using the constant curvature model. This position is then used together with available bending moment sensors located between the two segments of the manipulator to calculate the resulting hypothetical force acting on the tip. This approximation has been proved to be accurate enough for the carried out tests. In future, this approach will be substituted with real force sensors developed by consortium member [14].

A. Key concepts

There are several different sources of information that can be used in position estimation. First, two estimations can be calculated with the two available models: the Constant Curvature and the Bending Model. These two models base on different sensor data. Their outputs are statistically independent so that proper fusion should reduce the overall uncertainty. Each model error should also be estimated by separate algorithms. Another information which can be used in the data fusion procedure are various characteristics of the sensor output signals which indicate their noise level. For example, in a low external force situation it may be optimal to use the less accurate Constant Curvature model when the chamber length sensors' noise is lower in opposition to using the Bending Model based on pressure sensors.

Vision system is the third major source of information about the robots position. In the tight operating space only a fragment of the manipulator will be seen by the cameras. The images, after proper processing, will provide position of the visible fragment together with an error estimation. This data is very valuable for the fusion process, as it enables the position calculated with indirect methods to be refined by an absolute measurement.

The various system inputs are not updated continuously. One example is the vision system which is constrained by the frame rate and processing time. Therefore, the certainty of the position that the data fusion system produces at time T_0 should degrade over time. This is important for the other Stiff-Flop systems depending on the data fusion output that work at a different rate.

B. Data fusion system structure

The block diagram of the data fusion system is presented on Fig. 3. The block on the top of the figure represents all the available hardware described in paragraph 3. The chamber length sensor data is fed to the Constant Curvature model which calculates its position estimation. This position is used in data fusion block and in tip force approximation block which provides input to the Bending Model. Bending Model is also connected to chamber pressure sensors. It provides the second position estimation for the data fusion block. The uncertainty of each model is calculated dynamically by the appropriate error estimation block. The Bending Model precision is verified by comparison of the chamber lengths determined by the calculated shape with real chamber lengths. Since the Constant Curvature model is distorted by external mechanical interference, its verification is based on the measured values of forces and moments acting on the manipulator. The signal statistics blocks dynamically calculates parameters of all input signals providing information about their quality to the fusion procedure. The vision system uses the camera frames in order to produce the absolute position of a robot fragment with known uncertainty.

The data fusion algorithm merges all this information and outputs the final estimated manipulator position together with uncertainty. The overall procedure of merging n independent position information can be described by Equation 1:

Equation 1: General position fusion

$$\vec{P} = \frac{\sum_{i=1}^{n} (a_i p_i)}{\sum_{i=1}^{n} a_i}$$

The influence of each position estimation *i* is determined by coefficient a_i. Equation Y is applied to a fixed set of points along the robot spine. The coefficients are calculated on-line by algorithms that use various available information described earlier in this paper. After merging the positions, the estimation is refined using the output from the vision system. The error of the final position estimation is calculated using the errors provided by the calculation methods.

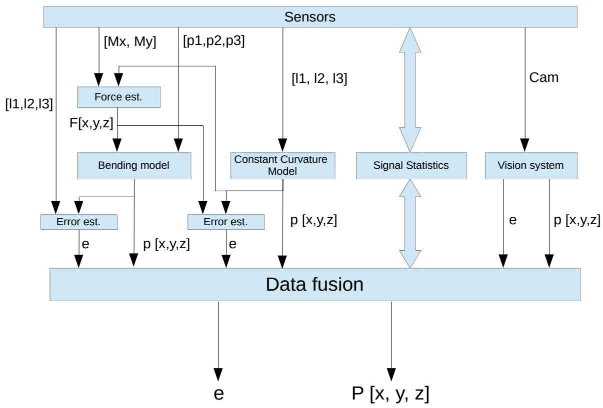

Fig. 3: Data fusion system block diagram

VI. Conducted experiments

In order to verify the concepts presented in this paper, a set of experiments had been carried out. First, interesting cases had been identified in simulated environment. Those cases were reproduced using real hardware. This procedure allowed performance assessment of individual available robot models and the data fusion algorithms at hypothetically problematic situations.

The first test case is when actuator chamber pressures are equal. The simulated scenario and real hardware test are presented on Fig. 4. Left hand side of the picture presents three point clouds representing module 'spines' calculated using different methods using simulated input data ran against the data fusion system. The red spine is calculated by the Constant Curvature model, the green is calculated by the Bending Model and yellow is the final data fusion system output. In this situation both models and data fusion give the same results – a straight robot module. This is consistent with the right hand side of Fig. 4.

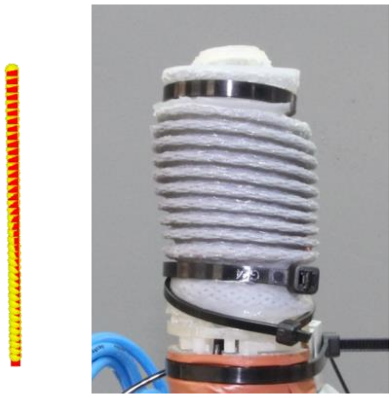

Fig. 4: Test case - straight, unbent module

Next, a pressure difference has been applied to the chambers. The situation is identical – both model results are consistent with the hardware. The module bends in a circular arc shape, as predicted by the Constant Curvature model. The results are presented on figure Fig. 5.

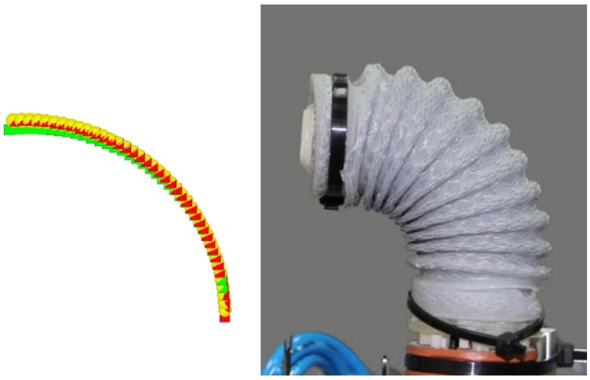

Fig. 5: Test case - module bent by pressures only

Figures 6 and 7 present results of module bending in two different directions by applying an external force. This displays discrepancies between model results. This time, the assumption of the Constant Curvature model is not fulfilled, thus the model does not give satisfying results. As it can be observed on Fig. 6**,** the robot shape is not a circular arc. The Bending Model exhibits better performance – the bend caused by external force influence is calculated. Because of the occurrence of the force, the error of the Constant Curvature model in the data fusion software is increasing, which causes its influence on the fused position to decrease. This can be observed on the left hand side of figure Fig. 7.

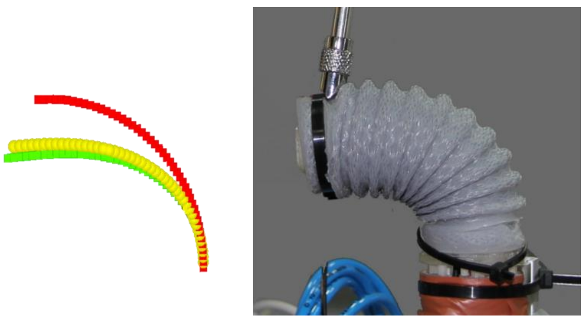

Fig. 6: Test case - module bent by external force

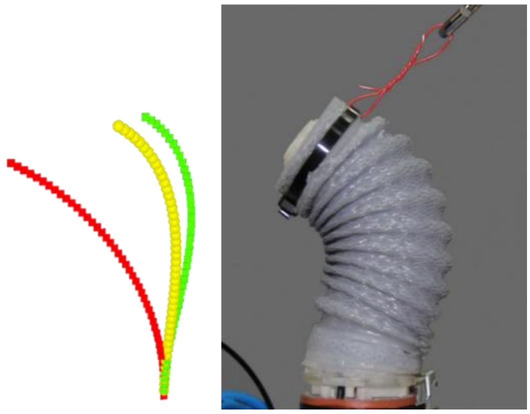

Fig. 7: Test case - module bent by pressures and external force

VII. Conclusion and Concepts for Development

The conducted experiments show that the performance and usability of different available robot models vary with the change of conditions, as there are many effects not implemented in the model (i.e. change of actuator chamber diameter when actuated). In an efficient data fusion system, these variations have to be considered. There are other factors which the fusion procedure should consider, such as sensor noise. The procedure has to have the ability to adapt to changes in the work environment (i.e. live sensor noise tracking).

The core problem in designing data fusion systems which are similar to the one described in this paper is the development of the algorithms which calculate the influence of each model results (see Equation 1). This can be done by manual design and testing. One concept for improving the coefficient calculation and thus, the data fusion system performance is through the use of machine learning. The algorithms which calculate the usability of a particular robot model at a given time can be based on neural networks taught in an offline calibration process. This idea is currently being explored by the authors for the use in the Stiff-Flop project data fusion system.

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DEMONSTRATION DURING THE WORKSHOP

During the ICRA 2014 Soft Medical Robots Workshop PIAP would like to present a 2 min teaser and poster presentation about the data fusion system design in the STIFF-FLOP project. Additionally, we would like to present the many challenges and limitations that the use of custom sensors imposes on estimating the manipulator position. We also would like to discuss the problems that arise from the novel mechanical structure of the STIFF-FLOP.

All tests described in this paper have been conducted using an experimental setup. The manipulator used for testing has been manufactured by the consortium member and equipped with the optical fiber sensors. The pressures are controlled with six electric valves, one per chamber. Those valves also provide the actual pressure value as their output. Optic sensors are powered by commercial amplifiers which output the received intensity. All data is collected by a microcontroller board and sent to a laptop computer through serial connection. The shape of the segment is controlled in an open loop using game pad connected to a laptop computer. The force is applied with a force gauge.

Because of the size of the setup, we would like to avoid shipping it to Hong Kong and present the data using the 2 min. teaser. The teaser would contain all the required elements to fully simulate the testing setup. It will present footage of the manipulator together with live data visualization from the fusion system (live plots, point clouds). Another interesting issue that will be presented on the teaser is the identification of the source of the model errors. For example, the error caused by the deformation of the actuation chambers or the source of sensor hysteresis can be visualized.

As it was stated above, the main topic of our demonstration would be data fusion system design and its main issues. Therefore, the poster will serve as a background for discussing these two topics. Figures 1 and 2 present concepts of what the teaser and the poster could contain.

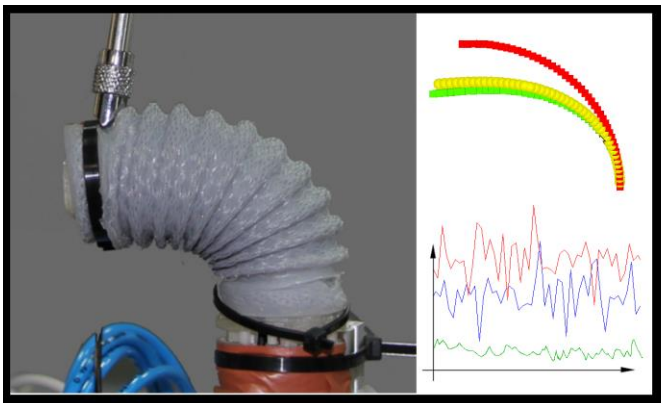

Figure 1 Example teaser screen shot

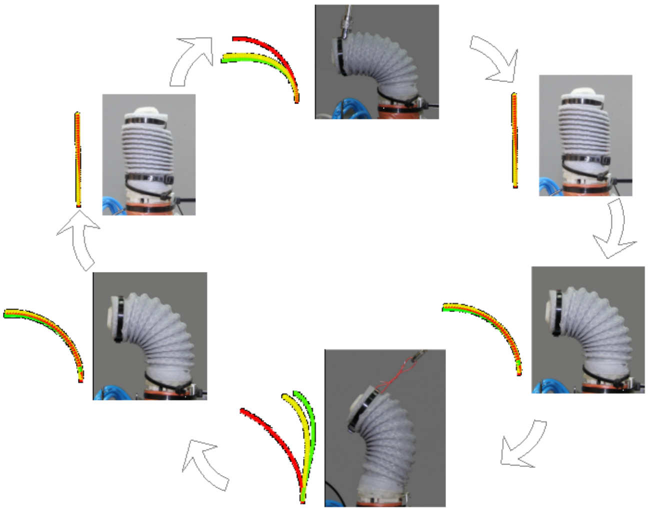

Figure 2 Example poster content

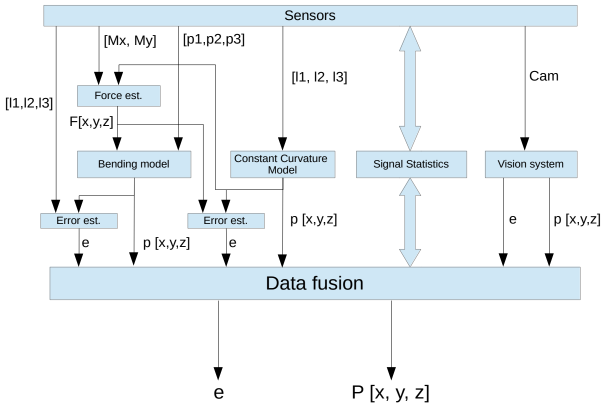

Figure 3. Data fusion system design block diagram for the poster