EFFICIENT ENERGY MINIMIZATION FOR MOTION COMPENSATION IN ROBOTIC SURGERY

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Abstract

The existing Robotic Surgical Systems have two drawbacks: i) lack of physiological motion compensation and ii) absence of force feedback. These issues are considered open problems due to the lack of robustness, efficiency and accuracy of the existing proposals. Thus, our research is focused on computer vision energy minimization methods, which allows approximating the heart motion via its surface deformation. Moreover, the capability of the Recurrent Neural Networks for predicting time series is used in order to deal with tool-tissue iteration.

Methodology

Motion compensation problem has been treated as an energy minimization problem, where $\ell 2-$ **and** $\ell 1-$ **Regularized Optimization classes** are tested. These have been implemented in 2D and 3D scenarios for soft object manipulation. Firstly, to compute the changes occurred on the tissue, B-splines are used, where a set of control points, $\mathbf{P}$, are defined. Parametrization of the disparity, d_m, is:

$$d_m(x;\mathbf{P}) = \sum_{j_1=0}^{n} \dots \sum_{j_d=0}^{n} \mathbf{P}_{j_1,\dots,j_d} \prod_{k=1}^{d} \beta_k(u_k)$$

where β_k are basis functions and x is a vector in $\mathbb{R}^d$. In the 3D case, if $I_l : \Omega_{I_l} \to \mathbb{R}$ and $I_r : \Omega_{I_r} \to \mathbb{R}$ are a pair of rectified images, the disparity map to be minimized, $\tilde{d_m}$, is computed as:

$$(*)\ \tilde{d_m}(\mathbf{P}) = \frac{1}{2} \sum_{x\in\Omega} (I_l(d_m(x;\mathbf{P})) - I_r(x))^2 + \zeta \sum_{i=1}^{d} \sum_{x\in\Omega} |\nabla d_m(x;\mathbf{P})|^2$$

where first term measures the discrepancy between the two images; second term restricts the solution in order to fulfill the Hadamard's postulate; ζ gives a balance between both terms; and x is a vector in $\mathbb{R}^d$. Minimization is carried out using Powell's dogleg method since it outperforms traditional methods, including Levenberg-Marquardt (LM).

To deal with the tool-tissue interaction issue, the proposal method uses **Vision-Based Force Estimation**, in which the central part to estimate the force vector is a **Recurrent Neural Network (RNN)**. The RNN is expressed as follows:

$$\tau_i \dot{f_{E_i}} + f_{E_i} = \sigma\left(b_i + \sum_j w_{ij} f_{E_j} + \sum_j w_{ij}\mathbf{S}_j\right)$$

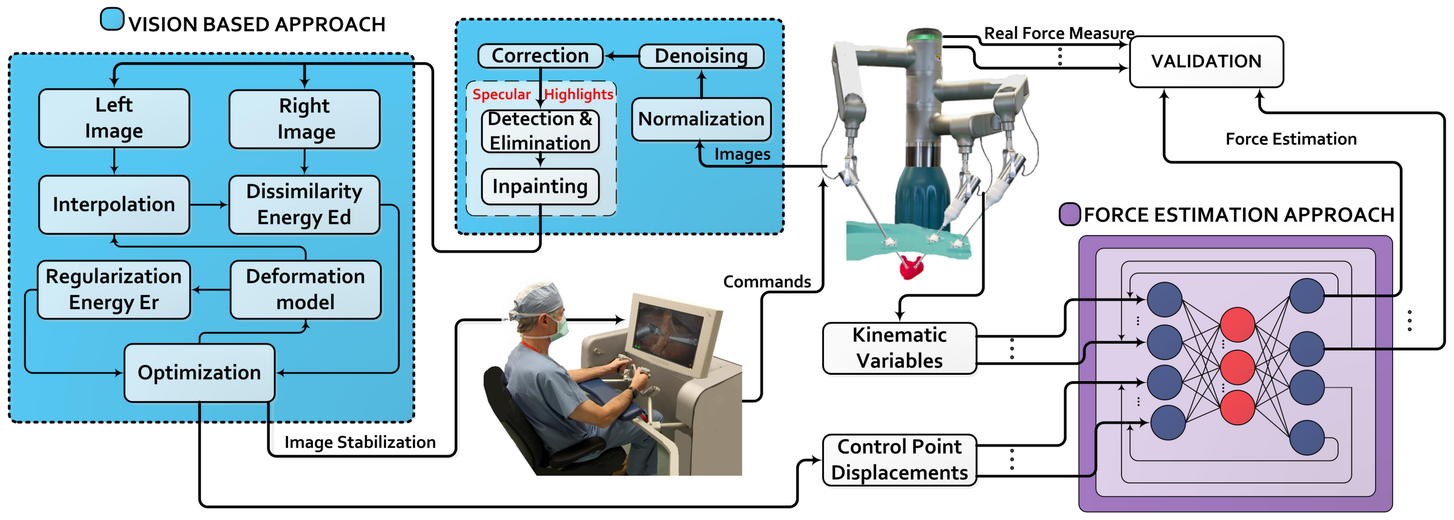
where f_E is the state variables of the i-th neuron; S_j denotes the external inputs ; σ is the activation function, w_{ij} the weights and b_i the bias.

$(*)$ The version in $\ell 1-$ is given by:

$$\tilde{d_m}(\mathbf{P}) = \frac{1}{2} \sum_{x\in\Omega} |(I_l(d_m(x;\mathbf{P})) - I_r(x))| + \zeta \sum_{i=1}^{d} \sum_{x\in\Omega} |\nabla d_m(x;\mathbf{P})| - \lambda \sum_{\mathbf{x}\in\Omega} log c_{\mathbf{x}}(d_m(x;\mathbf{P}))$$

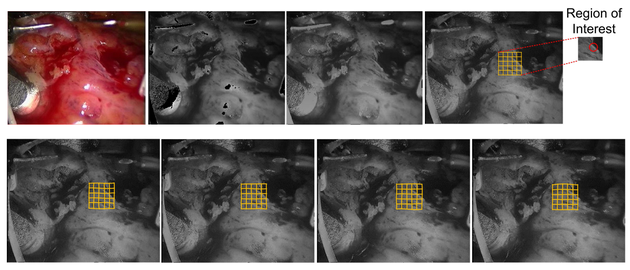
$\nabla u_1 = u_{i+1,j} - u_{i+1,j}$, $\nabla u_2 = u_{i,j+1} - u_{i+1,j}$, and $c_x(y) = y^2$

Proposed Scheme

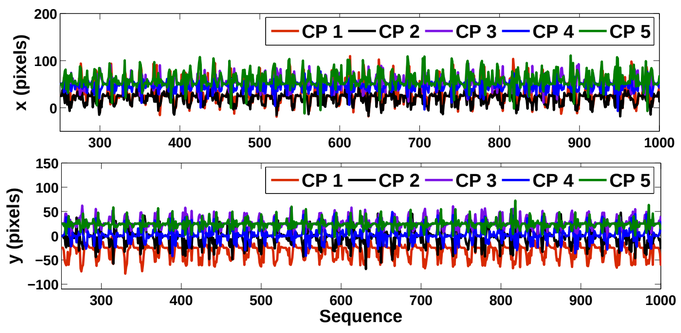


Experimentation Part

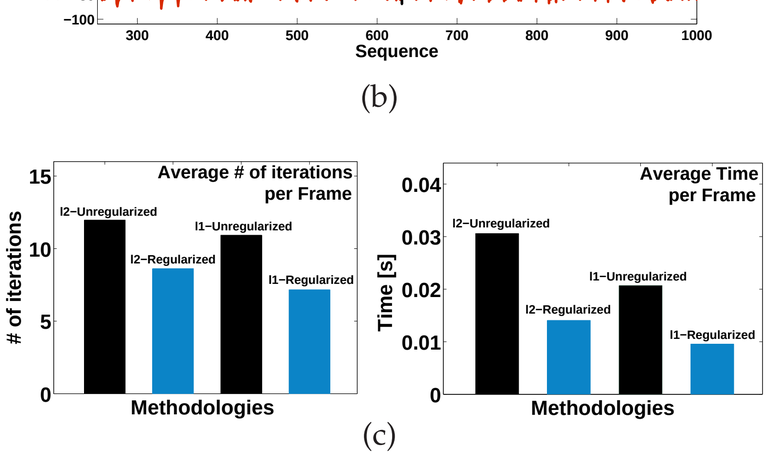
A. Results in 2D scenarios



(a)



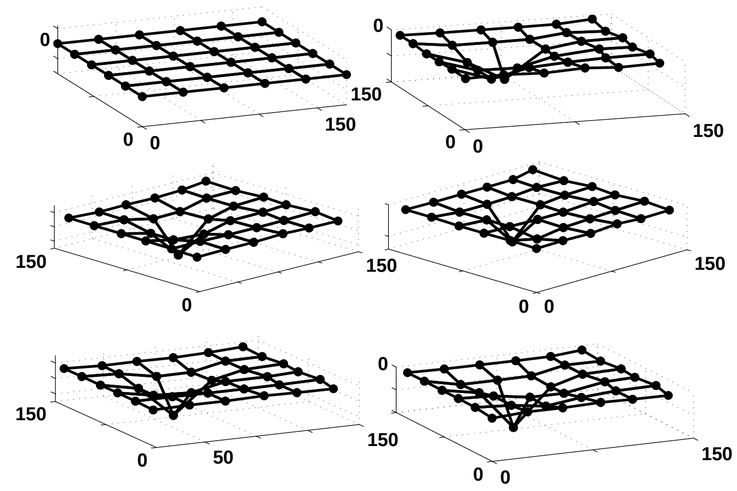
(b)



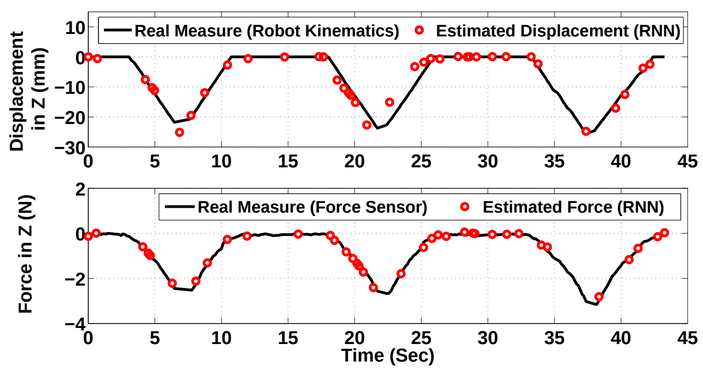
(c)

(a) Upper row (from left to right): an image of the sequence, detection and elimination of specular highlights, inpainting and selection of the zone of interest. Lower row: Behaviour of the approach; (b) Retrieved x- and y- coordinates of five control points (CP); (c) Computational performance;

B. 3D Vision Based Force Estimation



(d)



(e)

A. Vision Based Approach (DL)	
Average Time per Frame [sec]	Average #Iterations
0.0045	16
B. Mean Absolute Error	
Estimated Force (N)	Estimated Displacement (mm)
0.0464	1.3108

(f)

(d) Sequence of changes produced on the lattice when the force is applied; (e) Comparison between the real measure and the estimated: displacement (upper row) and force (lower row); (f) Performance Analysis.

Conclusion

According to the results obtained, our approach has demonstrated its potential in terms of efficiency and robustness working even under complex deformations and occlusions. In addition, the highlights of this proposal are: knowledge of material properties are not necessary, there is not need of adding extra sensors and avoid biocompatibility difficulties.