A model-based approach for tool tracking in laparoscopy

Potential applications and evaluation challenges

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A few words about the TIMC-IMAG CAMI team

Development of generic innovations Applications to several clinical fields for the past 20 years
CAMI team activities in laparoscopic surgery

• CAMI team activities in laparoscopic surgery:
  – Robotics
  – Multimodal navigation
  – Modeling of the surgical expertise

• Tool localization / tracking is an essential brick:
  – Tool localization can « augment » robotic commands
  – Tool localization can be useful for multimodal navigation
  – Tool localization can help understand surgical expertise
Talk outline

- Presentation of our tool localization method
- Presentation of a few applications
- Evaluation of the approach
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Tool localization: general framework

Hypothesis for now: the camera is fixed
Tool localization: general framework

Hypothsis for now: the camera is fixed
Tool localization: geometric model

$T$: 3D insertion point of the tool

Tool = cylinder of known diameter and length
Tool localization: camera calibration

- Provides the relationship between the tool model and the tool edges in laparoscopic images
- Can be computed using Zhang’s method in OpenCV
Tool localization: general framework

Hypothesis for now: the camera is fixed

CONSENSUS algorithm

- Determination of the instrument’s insertion point
  - Generation of particles on a geode centered on the insertion point
  - Determinist and Stochastic evolution of the particles
  - Reconstruction of the expected edges of the instrument in the image for each particle
  - Measure of a probability for each particle
  - Selection of the most probable particles
  - Localization of the tool tip

Geometric model of the instrument

Projection model of the camera (calibration)
Tool localization: determination of the tool’s insertion point (1/4)

- Knowing the tool’s insertion point in the camera frame reduces the number of dofs of the instrument

- “Pivot-like” method:
  - Detect the tool edges in the images using a non real-time method
  - Determine the corresponding 3D axis of the tool using the tool model and camera calibration
  - Use a SVD algorithm to find the best intersection point along with a RANSAC to eliminate outliers
Tool localization: determination of the tool’s insertion point (2/4)

• Method for detecting the tool’s edges in the image
  – Change of colorimetric space (HSV) [Doignon et al.]
  – Non linear filtering (to keep image edges) : bilateral filter
    • a study comparing the computation time for different filters was performed
  – Canny detector to detect image edges (with bilateral filter instead of Gaussian filter)
    • The parameters of the Canny detector (filter size, low+high threshold are automatically identified)
Tool localization: determination of the tool’s insertion point (3/4)

- Automatic determination of the “best” Canny parameters
  - Using a typical laparoscopic image
  - Statistical approach: find the parameters with best sensitivity & specificity [Yitzhaky and Peli, 2003]
Tool localization: determination of the tool’s insertion point (4/4)

- Probabilistic Hough transform to find the tool’s edges

- Reconstruction of the tool’s 3D axis for several positions

- Tool’s axes intersections (SVD) + outliers removal (RANSAC)
Tool localization: general framework

Hypothesis for now: the camera is fixed

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Geometric model of the instrument

Projection model of the camera (calibration)
Tool localization: search for the tool’s 3D orientation (1/2)

- Geode centered on the insertion point
  - A possible tool orientation corresponds to a cell on the geode
  - Easy discretization using geodesic grids

- Reduction of the search space using the Condesation Algorithm [Isard and Blake, 95]
Tool localization: search for the tool’s 3D orientation (2/2)
Tool localization: search for the tool’s 3D orientation (2/2)

- Determinist evolution
- Stochastic evolution
- Image Measurement
- Sampling

\[
\{ s_t^{(n)}, \pi_t^{(n)} \}_{n \in N}
\]

\[
\{ s_{t+1}^{(n)}, \pi_{t+1}^{(n)} = 1 \}_{n \in N}
\]

Probability density at time t+1

\[
\{ s_t^{(n)}, \pi_t^{(n)} \}_{n \in N}
\]
Tool localization: search for the tool’s 3D orientation (2/2)
Tool localization: search for the tool’s 3D orientation (2/2)
Tool localization: search for the tool’s 3D orientation (2/2)
Tool localization: search for the tool’s tip

- Last dof to be determined: insertion depth
  - Exploration of a sliding window on the tool’s axis
  - Measure of inter-class separability [Otsu algorithm]
Tool localization: video example
Talk outline

- Presentation of our tool localization method
- Presentation of a two potential applications
- Evaluation of the approach
First application: visual servoing of a robotic endoscope holder

[A. Agustinos, PhD student]

- The insertion point is estimated when the camera moves thanks to the hand-eye calibration of the robot.
Second application: analysis of surgical gestures [R. Wolf, PhD student] (1/2)

- The “Fundamentals of laparoscopic skills” based on the MISTEL testbench used to analyze the quality of execution of basic laparoscopic tasks

- Adopted for the evaluation of interns in digestive surgery

- Score based on execution time and gesture precision measurements

- Tool localization could be used to automatize this grading

- Could help acquire a finer understanding of surgical expertise
Second application: analysis of surgical gestures [R. Wolf, PhD student] (2/2)

- In this frame, data acquisition was performed for:
  - 13 Med students, 8 residents, 11 surgeons
  - Tool localization was performed offline
  - A Polaris system was used for “ground-truth” measurements (the participants were asked to not pay attention to the Polaris)
  - A systematic registration error between Polaris / camera data was detected – a rigid registration was performed on the data for comparison

![Image of data acquisition process]

- Raw measurement
- After outliers removal
- After spline smoothing
Talk outline

• Presentation of our tool localization method

• Presentation of a two potential applications

• Evaluation of the approach
Evaluation of the approach (1/4)

- Precision of the insertion point computation

In practice, we re-evaluate the insertion point during tool tracking by incorporating Gaussian noise.

10 computations
Red circle: gravity center of the measurements
Green circles: the 10 measurements
Mean error: 6mm
Evaluation of the approach (2/4)

- **Computation time considerations:**
  - On a Intel Xeon PC 2.67 GHz, 3.48 GB RAM
  - in C++ (release mode)
  - The most important parameters is the number of particles in the Condensation algorithm

  ![Graph showing frequency (Hz) vs. number of particles for different background conditions.](image)

  - The geode can have a “big” resolution because it is computed only once at initialization.

  - Compromise depending on the application and required precision.
Evaluation of the approach (3/4)

• Precision considerations:
  – In theory, a ~ 650 000 cells grid allows for a resolution of 0.47 mm for a tool insertion depth of 100 mm and 1.41 mm for an insertion depth of 300 mm
  – 2D tool orientation vs. manual labeling: error <1° with 1000 particles
  – 2D tool tip vs. manual labeling (on 20 images, with 1000 particles): mean error of 7.6 pixels on a 720x480 image
  – 2D tool orientation vs. Polaris (after compensation of the registration error):

![Graph showing angular error in 2D vs. number of particles for different backgrounds](image)
Evaluation of the approach (4/4)

• Precision considerations:
  – 2D tool tip vs. Polaris (after compensation of the registration error): results not so good with an average error of 20 pixels on white background and 50 pixels on surgical background
    • Could be due to occasional confusions between tool tip and tool shaft
    • A small error in axis detection can lead to a big error at the tip
    • Our simple thresholding method should be replaced/improved
  – 3D orientation vs. Polaris:
    Errors for orientation in 3D when 2D orientation seems « perfect » due to errors along camera’s optical axis
    In some configurations, a 1 pixel error in the image detection can lead to a >2 mm tip error in 3D
Conclusions / Perspectives

• Tool localization / tracking method
  – That can be “real-time”
  – That can (not very precisely) localize tools in 3D based on 2D image analysis
  – The 3D precision could be drastically improved with a stereo-endoscope
  – We need to improve the tool tip localization precision / robustness

• Evaluation issues:
  – Image-based measurements are good but not enough!
  – Polaris-based measurements are complicated (setup, calibration/registration issues, missing data issues: visibility of tools without changing practice?)
  – How can we make better quantitative evaluations?

• Some example of applications
  – Our next step is to test the localization method / visual servoing during cadaver experiments
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