Intra-Operative Position Sensing and Tracking Devices

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INTRODUCTION

Intra-operative position sensing and tracking devices are fundamental building blocks which are often used in Computer-Assisted Orthopaedic Surgery (CAOS). These devices are used during surgery to precisely localize conventional surgical tools, rigid anatomical structures, other medical imaging equipment (e.g., X-Ray or ultrasound scanners), surgical implants, etc. For example, in computer-assisted spine surgery, it may be desirable to determine the position and orientation of a drill relative to a vertebral body. Intra-operative sensors can be used to independently measure the locations of the vertebral body and the drill, and then the relative position and orientation can be inferred. In this abstract, the term *position sensor* refers to a type of sensor which can localize one or more discrete points in 3-D space. Such sensors can also compute object orientation when 3 or more measured points are attached to a single rigid object. The term *surface sensor* refers to a type of sensor which can measure the bounding surface of an object (e.g., the surface of a bone). In this abstract, characteristics and examples of both sensor types are presented.

SENSOR CHARACTERISTICS

There are a number of attributes which characterize a given intra-operative sensor including the quantity being measured (e.g., position, orientation, surface mapping), sensing modality, accuracy, resolution, speed, robustness, contact vs. non-contact, active vs. passive, and cost. Sensing modality refers to the general class to which that sensor belongs (e.g., mechanical, optical, acoustic, magnetic, X-Ray based, etc.). For any sensor measurement, there is a *correct* value which that measurement would have in an ideal world (i.e., a world with no measurement noise or errors). Since such correct values are unknown in general, all sensor measurements are *estimates* of the corresponding correct values. Sensor *accuracy* is a measure of the difference between estimated and correct measurement values. A sensor's *resolution* represents the smallest change which can be detected by the sensor. The speed of a sensor can be characterized by two parameters: *bandwidth* and *latency*. Sensor bandwidth is a measure of the amount of information which can be acquired and processed by the sensor per unit time and is typically measured in cycles per second or Hertz (Hz). Sensor latency is the delay between the beginning of the measurement process and the time at which the measurement data is available for subsequent processing. The *robustness* of a sensor is a qualitative measure of reliability and the degree to which the sensor is vulnerable to interference. Other sensor attributes include: whether or not the sensor comes into physical contact with the object being measured; whether the sensor is *active* (i.e., emits energy in the form of visible light, sound, X-Ray radiation, etc.) or *passive* (i.e., does not emit energy). Finally, sensors vary in terms of the associated fixed and variable monetary costs. Selecting a particular intra-operative sensor for a given application is a complex process which involves assessment of each of the above attributes relative to requirements of the task.

SENSOR MODALITIES

Modalities which are commonly employed in position and orientation sensors include mechanical, optical, magnetic, and acoustic mechanisms. *Mechanical* sensors determine the position of a sensor endpoint based upon measurements of joint angles and information regarding the kinematics of the device. *Optical* sensors track the positions of one or more actively illuminated markers and use geometric triangulation to determine the locations of these markers. Recently, systems using passively illuminated reflective markers have become popular as well. *Magnetic* sensors measure electrical currents induced in receiver coils when the receiver is moved within a magnetic field generated by the emitter. *Acoustic* sensors receive signals which are emitted by ultrasonic emitters and determine location via time-of-flight. A comparison of these sensing modalities is presented in Table 1.

Table 1: Comparison of Position / Orientation Sensing Modalities

	Mechanical	Optical	Magnetic	Acoustic
Accuracy	0.1 - 2.5 mm	0.1 - 0.5 mm	~5 mm	~1 mm
Resolution		best ~0.01 mm		~ 0.1 mm
Bandwidth	>3000Hz	100-2500 Hz	20-100Hz	500-1000Hz
Interference Sources	physical occlusion	heat, occlusion	ferrous objects, magnetic fields	temp., humidity, occlusion
Examples	Faro Arm, NeuroNavigator	Optotrak 3020, Flashpoint	Polhemus, Flock of Birds	Sonic Wand
Contact / Non-contact	Direct Contact	Contact w/ targets	Contact w/ targets	Contact w/ targets
Passive / Active	Passive	Active	Active	Active

The position sensing modalities described in Table 1 can measure relatively small numbers of discrete 3-D points. A digitizing probe can be attached to any of these sensor types to allow the measurement of discrete points on the surfaces of exposed, rigid anatomical structures. Unlike position sensors, *surface* sensors can measure dense sets of points on the surfaces of anatomical structures without direct contact between the sensor and the measured object. Modalities used for surface sensing include passive stereo, active range, 2.5D ultrasound, X-Ray, and real-time MRI. *Passive stereo imaging* uses 2 or more cameras to view a scene. The disparity between corresponding points within the multiple images is used to infer the 3-D location of the points. *Time-of-flight* active range imagers measure the time required for a laser to reflect off a point on an object and return to the imager. *Structured-light* active range imagers project a pattern of light onto an object and infer 3-D location based upon the computed intersection between the light and the sensed object. *Shape-from-focus / defocus* imagers rely on the relationship between the distance from sensed object to camera lens, and the degree to which the object is in focus within the imager. A comparison of surface sensing modalities is presented in Table 2.

Table 2: Comparison of Surface Sensing Modalities

	Passive Stereo	Active Range	2.5D Ultrasound	X-Ray
Accuracy	~1 mm	0.5-1.0 mm	~1.0 mm	~0.5 mm
Resolution	best ~0.01 mm		~1.0 mm	
Bandwidth	1000 points/sec to 30 video image/sec	0.1-1000 Hz	0.1-0.5 Hz (segmentation req'd)	slow
Interference Sources	ambient light, metal reflectors occlusion	metal reflectors occlusion	metal, bone	
Examples	VISLAN, Video-rate stereo	Light-stripers, CMU range sensor	Phased-arrays	Polhemus, Flock of Birds
Contact / Non-contact	Non-contact	Non-contact	Non-contact	Non-contact
Passive / Active	Passive	Active	Active	Active / radiation

A relatively new type of intra-operative sensor which is currently being used in several research hospitals is interventional magnetic resonance imaging (IMRI). IMRI allows a clinician to guide, monitor and control therapeutic interventions or minimally invasive surgical procedure while viewing MRI images of the relevant anatomy and tools in near real-time.

CONCLUSION

Intra-operative position sensing and tracking devices are integral components in most existing computer-assisted orthopaedic surgical systems. A brief list of references and introduction to the literature follows.

REFERENCES

[1] Azuma, R.T., "A Survey of Augmented Reality", SIGGRAPH '95 Course Notes, Aug. 1995.

[2] Barnett, G.H. et al., "Frameless Stereotaxy Using a Sonic Digitizing Wand: Development and adaptation to the Picker ViStar Medical Imaging System" in *Image-Guided Neurosurgery* (R.J. Maciunas, M.D., ed.) ch 10 pp 113.

[3] Besl, P., "Range Imaging Sensors", General Motors Research Publication GMR-6090, March 8, 1988.

[4] Bucholz, R.D. et al., "A Comparison of Sonic Digitizers vs. Light Emitting Diode-Based Localization", in Image-Guided Neurosurgery (R.J. Maciunas, M.D., ed.) ch 16 pp 179.

[5] Grimson, W.E.L. et al., "Evaluating and Validating an Automated Registration System for ENhanced Reality Visualization in Surgery", in *Proc. Computer Vision, Virtual Reality and Robotics in Medicine (CVRMed '95)*, Springer Lecture Note 905, pp 3-12, Nice, April 1995.

[6] Kanade, T., et al., "A very fast VLSI Rangefinder", in *Proc. IEEE Int'l Conf. on Robotics and Automation '91*, Sacramento, CA, April 1991.

[7] Lavallee, S., et al. "Computer-assisted Spinal Surgery using Anatomy-based Registration", in *Computer-Integrated Surgery* (R.H. Taylor, G.C. Burdea and R. Mosges, eds), pp 425-449, 1996.

[8] Meyer, K., Applewhite, H.L. and Biocca, F.A., "A Survey of Position Trackers", Presence 1(2), Spring 1992.

[9] Northern Digital Inc., Home Page - http://www.ndigital.com/