SENSOR ARCHITECTURE FOR MOBILE CONSTRUCTION ROBOT

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ABSTRACT

The operation of a semi-autonomous self-guiding mobile construction robot under real building construction environment, is heavily relied on a sensor based intelligent hierarchical control system. A multi-sensor architecture consists of variery of sensor types and technologies is proposed. The architecture is designed to meet both the operational as well as the mission specific sensing requirements. Because of volume limitations, data processing issues are not covered in this paper.

INTRODUCTION - THE NEED FOR SENSORS

A semi-autonomous self-guiding mobile construction robot (MCR) is designed to work within an organizational framework and under mission and environment conditions which are significantly diffrent from the working and the environment conditions of most industrial robots (IR) which are currently used on the shopfloor.

The major factor which distinguish between the sensing requirements of MCR and these of IR are:

Task definition: To be used effectively,the MCR should be programmed using a goal-driven task-level programming tools. Current IR does not meet this level of programmability.

Mobility: The MCR will conduct its tasks within a geometrical envelope much larger than its own working envelope. To meet this need, the robot should be mobile. The MCR is designed to move safely between the working stations while navigating autonomously within the working area. Most IR are either immobile or its mobility is limited to predetermined routes.

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Spatial range and accuracy: Most IR has moderate spatial dynamic range. The spatial positioning acuuracy is achieved by using rigid heavy weight manipulator structure. The MCR will require larger spatial dynamic range. The spatial positioning accuracy of the MCR should be achieved even in the case of using flexible light weight manipulator arms, to save volume and weight.

Task and process organization: Current generations of IR are designed to work on a structured task under well defined process variables and organized environment and materials supply. The MCR should be capable of performing unstructured tasks in lowly organized environment characterized by uncertain changing conditions. Also, while most IR work in a permanent location, the MCR will work only once, per task, at a certain location.

Process control: In-process quality control capability is significant for the operation of the MCR in most of his tasks. Most IR does not involve this capability.

SENSOR CLASSIFICATION

The sensors supporting the operation of the MCR can be classified as follows:

Supported task

- Sensors supporting general operation.
- Sensors supporting specific building construction tasks.

Function

- Sensors monitoring the performance, status and health of MCR internal sub-systems.
- Sensors for world perception and robot-environment relationship monitoring.

SENSOR FUNCTIONAL REQUIREMENTS

The sensor functional requirements per MCR's task are listed in the following tables.

Robot task	Task representation		Functional requirements
	global	local	
Autonomous moving between workstations	+	+	* global & local location and orientation for free navigation * obstacle detection and collision avoidance
In-station positioning and alignment	+	+	* robot location and orientation in global & local grid for task coordination and alignment
operational safety		+	* obstacle detection within arm working envelope * emergency detection
operation monitoring	internal	internal	* system control * sub-systems performance monitoring * sub-systems status and health monitoring

Table 1 : Sensor functional requirements - general operation

Robot task	Task representation: global	Task representation: local	Functional requirements	Materials location	process quality control
Wall building	+	+	* wall location in global & local grid * block laying $ positioning control * wall & openings boundry detection * block position in a supply pallet * cement flow control	+	
Surface coating & finishing		+	* distance-to-surface measurement * wall & openings boundry detection * coating thickness gaging * finishing / polishing force control		+
Joint / groove sealing & finishing		+	* joint boundry tracking * material filling control		+
Construction elements welding		+	* seam location * seam tracking		+
grooving & groove filling	+	+	* groove orientation & location * groove depth & width measurement * filling level monitoring * grooving force monitoring		+

<u>Table 2 : sensor functional requirements - mission specific</u>

OPERATIONAL REQUIREMENTS

In addition to meeting the functional and the performance requirements, the operational requirements are recommended as guidelines for designing the sensor system. The operational requirements are as follows:

- robust operation in all operational scenarios.
- sensor failure will not affect operational safety.
- sensors calibration will be conducted automatically.
- sensors will support multiple of tasks.
- sensor off-line programmability.
- flexible sensor architecture to enable sensor system reconfiguration.
- build-in-testing.

DESIGN CONSIDERATIONS

Various factors should be concidered throughout the design process both at the system architecture level and at the hardware sub-systems and component level. The factors to be concidered are:

- sensing capability
- performance under real environment conditions.
- dynamic response time.
- sensing error sources.
- data processing requirements.
- interface compatibility.
- hardware off-the-shelf availability.
- price.
- life-cycle-cost.
- reliability.
- maintenability.
- requirements for on-site preparations.

SENSOR TECHNOLOGIES

Sensors for semi-autonomous navigation

Sensor functions

- global and local location and orientation data.
- obstacle detection and collision avoidance.

In order to achieve safe self-guided navigating capability, the MCR should be provided with global position and orientation information continuously. Also, real-time information on the presence of in-path obstacles is required while the robot is moving between workstations.

The navigation sub-system will be based on a combination of two approaches. Position-Fix navigation to achieve site-related bounded error position and orientation information,both globally and locally. Dead-Reckoning naigation to provide continuous, self-contained position and orientation information between successive Position-Fix updatings and in cases that the Position-Fix system is not effective.

Alternative methods for Position-Fix navigation are listed in the following tables. The methods are based on the measurement of either angles or angles and distances from the robot to reference points, the location of which is known.

#	Method	Technology	Equipment location
1	electro-optical beacons	electro-optics	* transmitter - working site * receiver - robot
2	electro-optical beacons	electro-optics	* transmitter - robot * reflectors - working site * receiver - robot
3	electro-optical beacons	electro-optics+ autocolimation	* transmitter - robot * receiver+autocolimator - robot * reflectors - working site
4	RF beacons	radio-frequency	* transmitter - working site * receiver - robot
5	RF beacons	radio-frequency + transponders	* transmitter - robot * receiver - robot * transponders - working site
6	imaged passive coded targets	optical imaging	* imaging sensor - robot * coded targets - working site
7	scanned passive coded targets	laser scanning	* laser scanner - robot * coded targets - working site
8	range measurements	electro-optical interferometry	* tracking transmitter - working site * tracking receiver - working site * tracking mirrors - robot
9	automatic theodolites	optical	* automatic tracking theodolites - working site * targets - robot

Table 3 : General alternative methods for Position-Fix

#	Method	Technology	equipment location		Angular resolution	Effective range	Estimated cost
			on-site	robot	[mRAD]	[m]	[$]
1	passive uncoded reflective targets	electro-optics	reflectors	transmitter + receiver	30	15	600
2	passive uncoded reflective targets	electro-optics + autocolimation	precise mirrors	transmitter + receiver	0.001	10	8000 +
3	active electro-optical beacons	electro-optics	LED transmitters	CCD camera + zoom	1	10	1000
4	imaged passive coded targets	optical imaging	coded targets	CCD camera + zoom	1	10	1000
5	scanned passive coded targets	laser scanning	coded targets	laser scanner	1	6	2500

Table 4 : Alternative methods for Position-Fix

The estimated costs are based on vendor data. It does not include cost of site equipment and cost of site preparation. Cost of the associated data processing equipment is also excluded.

Position-Fix methods #4 or #5 are believed to be the most cost-effective working solutions.

Dead-Reckoning navigation is based on accumulation of measured incremental directed distances from a reference starting point. Two independent measured variables are required : travelled distance and travelling direction.

Alternative methods for travelled distance measurement are:

- measurement of robot wheels motion.
- measurement the motion of add-on undriven free castor wheel.

Alternative methods for travelling direction measurement are:

- gyrocompass.
- magnetic direction finder (e.g. flux-valve).
- directional gyro.
- add-on undriven free castor wheel.

The first method provides geographic related information, while the other methods provide only relative direction information.

Since the assumed steering method of the robot is skid steering, the associated slippage elimenates the wheels motion measurement as a method for true distance measurement.

Two shaft encoders, one at the castor wheel rotation axis and one at the castor azimuth axis, will provide the true travelled distance information as well as the direction information. Special arrangement at the free castor wheel will ensure reliable direction data.

The navigation processor will fuse the Position-Fix information with the Dead-Reckoning information to provide reliable continuous navigation capability.

To enable collision-free self-guiding movement and for operation safety, the MCR will be capable of detecting obstacles on its planned path. A surrounding ultrasonic rangefinders array, will provide a safety envelope all around the robot. In addition, a tactile pressure activated strip switch along the cart perimeter will provide a short distance safety mean.

A minimal configuratin is required for obstacle detection and collision avoidance. A full automatic obstacle avoidance capability requires more powerful navigation planning capability ob-board.

Sensors for in-station positioning and alignment

Sensor functions

- information on robot location and orientation in site related global grid for task coordination and alignment.
- relative location and orientation information with reference to local environment.

In-station positioning and alignment will be based on two methods. One is Position-Fix combined with Dead-Reckoning as used for navigation between workstations. The second method is to use the cart mounted array of ultrasonic rangefinders as well as the arm mounted ultrasonic rangefinders to provide locally referenced location and direction data.

Sensors for operational safety

Sensor functions

- obstacle detection.
- emergency detection.

To enable collision-free continuous operation and to eliminate any possible damage or hazardous situation, it is required to detect any obstacle or disturbance within the MCR manipulator working envelope. The environment close to the robot is scanned and existing obstacles are detected by two arrays of ultrasonic rangefinders. One array will be located along the cart perimeter, and will be used for navigation safety also. Another array will be located on the arm links and will provide omni-directional safety envelope attached to the arm.

The detection of emergency to any person or piece of equipment within the MCR danger envelope will be based on quadruple sensor array:
- an ultrasonic sensor array along cart perimeter.
- an ultrasonic sensor array attached to the manipulator arm.
- a perimeter tactile pressure activated strip switch.

- a portable safety optical light barrier placed along the working area. Any crossing of the projected planes will activate the system safety measures. As the MCR is moved to a new working area, the optical barrier is manually relocated.

Sensors for operation monitoring

Sensor functions

- providing data for system control.
- performance monitoring.
- sub-systems status and health monitoring.

Many of these sensors are similar to the sensors used in IR. Other sensors in this group are required for monitoring the drive and the locomotion sub-systems. In case of using flexible arm structure, additional sensors will be required for active structure deflection control.

Sensors supporting wall building

Sensor functions

- wall location in global grid.
- block positioning and laying control.
- wall and oppenings boundry detection.
- block position in the supply pallet.
- cement flow control.

Alternative methods for wall location are listed in the table below.

#	Method	Technology	Equipment		Wall location accuracy	End effector distance to markers	Estimated cost
			on-site	robot	[mm]	[m]	[$]
1	passive standoff targets	optical imaging	reference targets on surfaces or floor	CCD camera + zoom on arm tip	+/- 10	5	1000
2	active beacons	electro-optics	LED transmitters	CCD camera + zoom on arm tip	+/- 10	5	1000
3	light surface	electro-optics	laser light plane projection	detectors on arm tip	+/- 5	5	4000
4	wall line tracking	electro-optics	wall line marked on floor	proximity light tracker on arm tip	+/- 1	0.1	200

Table 5 : Alternative methods for wall location

Block placing and alignment will be supported by a combination of multiple of sensors. The contour of the blocks next to the layed block will be recognized by an imaging sensor (e.g. CCD camera) attached to the arm tip. The wall plane will be recognized by an array of either tactile switches or ultrasonic proximity sensors. Further alignment information will be provided by measuring forces and moments acting on the end-effector throughout the block laying phase. Vertical plane alignment will be monitoring by using either a two-axis electronic inclinometer or two single-axis devices. Block position in a supply pallet will be recognized in two phases. First, locating the randomly placed pallet and then, to locate a block within the pallet. Special coded marks attached to the pallet will support pallet location and orientation to enable arm guidance.

Sensors supporting surface coating and finishing

Sensor functions

- range-to-surface measurement.
- surface boundry and discontiuity detection.
- coating thickness gaging.
- finishing and polishing force measurement.

Range-to-surface control is required to achieve homogenous coating layer for economical and quality reasons. Feasible technologies are ultrasonic range measurement or triangulation electro-optical range finder. For this application, an array of ultrasonic rangefinders with automatic air-velocity compensation is very cost-effective. Achieveable range accuracy is +/- 1 mm for 1m range. Cost per sensor is in the range $250 - $350. Surface boundry and opennings will be recognized by using an arm mounted CCD camera. Lighting means might be required in case of low contrast between the surface and the opennings background. Coating thickness gaging can be performed by one of several methods. Indirect thickness control is based on both tight range and coating material flow control. Another indirect method is to measure the range-to-surface closely ahead and closely behind the coating gun simultaneously. Direct thickness gaging methods are based on either capacitance measurement or on acoustic wave propagation in the coating layer. However, for effective use of these technologies, a continuous contact with the coating layer is required. Non-contact thickness gaging with current technologies is effective in very short range only. A 6 DOF moment and force sensor, mounted in-between the wrist and the end effector will provide the dynamic reactions information.

Sensors supporting joint/groove sealing and finishing

Sensor functions

- joint or groove boundry tracking.
- material filling control.

A combination of an imaging sensor emoloying a CCD camera and a light-plane projector provides the information required for boundry tracking, center line tracking, as well as material filling control. The camera and the light-plane projector will be mounted on the top of the arm.

Sensors supporting construction elements welding

Sensor functions

- seam location.
- seam tracking.

Seam location will be determined relative to passive coded targets which will prepositioned on the building elements. A vision system will provide the MCR with guidance capability. It will support bringing the welding gun and the seam tracking device to its acquisition basket. Seam tracking capability is needed for welding construction elements. Commercially available systems can provide 3D tracking with accuracy of +/- 0.3 mm and with initial position deviation of up to 60 mm. Two most popular seam tracking technologies are electromagnetic induction currents and laser-based electro optical scanning rangefinder. Commercial products are ruggedized against welding heat, high currents interference and smoke. The selected method should track all joint geometries. A comparison between these technologies is given in the following table.

Technology	Tracking accuracy [mm]	Initial position deviation [mm]	Maximum distance from surface [mm]	Estimated cost [$]
Electromagnetic induction current	+/- 0.3	+/- 30	10	3000
Electro-optical scanning range measurement	+/- 0.1	+/- 60	50	25000

Table 6 : Alternative methods for seam tracking

Sensors supporting grooving and groove filling

Sensor functions

- groove location and orientation.
- groove depth monitoring.
- filling level monitoring.
- grooving force monitoring.

Various methods for groove location at site related grid are listed in table 7.

Groove depth will be controlled by a combination of a proximity switch and a mechanical stopper. An electro-optical reflective proximity switch can meet the needs. Groove filling monitoring will be similar to joint filling monitoring.

A 6 DOF, 3 force vectors and 3 moment vectors, will be mounted between the end effector and the mounting plate at wrist tip.

#	Method	Technology	Equipment on-site	Equipment robot	Location accuracy [mm]	Markers - arm tip range [m]	Estimated cost [$]
1	passive coded targets	optical imaging	reference lines on surfaces	CCD camera + zoom	+/- 10	5	1000
2	active beacons	electro-optics	LED transmitter	CCD camera + zoom	+/- 10	5	1000
3	light plane	electro-optics	light plane projector	electro - optical detector	+/- 5	0.05	4000
4	marked guiding lines	optical tracking	marked lines along groove perimeter	proximity sensor at arm tip	+/- 1	0.05	200

Table 7 : Alternative methods for groove location

DATA PROCESSING

The proposed sensor architecture should be supported by an appropriate data processing and perception capability.

The data processing issues are beyond the scope of this paper and are subject to a follow-up paper. Relevant issues are:

- data processing algorithms.
- processing architecture,e.g., central vs. distributed processing.
- data processing hardware.
- sensor programmability.
- sensor calibration.
- I/O and communication requirements.

It should be mentioned that the perception complexity in building construction environment is relaxed compared to general world modeling due to the following factors:

- semi-controlled environment relevant conditions.
- simple geometries.
- most sensed variables can be processed as vector quantities rather than matrix/array quantities.

PROPOSED SENSOR CONFIGURATION

A sensor configuration is proposed for a MCR . This configuration is open and flexible so changes in tasks to be performed by the MCR can be met by appropriate changes in sensor configuration.

The sensors and associated accessories are listed in the following tables.

#	Sensors	No. of sensors	Sensors location
1	distance measurement wheel	1	underneath chassis
2	CCD or CID camera + zoom	1 - 2	cart deck
3	CCD or CID camera + zoom	1 - 2	manipulator forearm
4	tactile safety strip switch	1 - 2 arrays	cart perimeter
5	ultrasonic rangefinder	4 - 8	cart perimeter
6	ultrasonic rangefinder	4 - 8	manipulator arm
7	ultrasonic rangefinder	4 - 6	block gripper
8	ultrasonic rangefinder	3 - 4	surface coating end effector
9	proximity switches	2	grooving end effector
10	proximity switches	4 - 6	block gripper
11	6 DOF force/moment sensor	1	between wrist and end effector
12	seam tracking sensor	1	attached to welding gun

Table 8 : Proposed sensor configuration

CONCLUSIONS

A sensor architecture is proposed to support the operation of a semi-autonomous mobile construction robot.

All proposed sensors are commercially avaiable, at least at the front end sensing level. However, extensive effort is still required to develop the associated algorithms, real-time software and hardware for data processing and data interpretation.

REFERENCES

[1] Warszawski,A.,"Application of Robotics to Building Construction", Carnegie Mellon University,PA.,U.S.A.,and The Building Research Station, Technion,Haifa,Israel, 1984.

[2] Evans,J.M.,"Measurement Technology for Automation in Construction and Large Scale Assembly",Proceedings of a workshop,National Bureau of Standards,U.S.A., Report # NBSIR 85-3310, 1985 .

[3] Batchelor,B.G.,et al.,Ed.," Automated Visual Inspection", IFS Publications, 1985 .

[4] Yavnai,A.,"Conceptual Design for Semi-Autonomous Mobile Construction Robot",AGA SERVOLEX LTD.,Report # DT-RN-86-4340, November 1986.

[5] Yavnai,A.,"Feasibility Study for Autonomous Mobile Security Robot", AGA SERVOLEX LTD.,Report # DT-RN-86-4350, December 1986 .

[6] Yavnai,A.,"Navigation Modes in Mobile Autonomous Robots",in Proceedings of The 21th Israel Conference on Mechanical Engineering, Haifa, Israel, June 1987.