Practical Sensor Strategies for On-Site Positioning of a Mobile Bricklaying Robot

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ABSTRACT

The authors describe practical sensor systems suitable for a mobile bricklaying robot for automated masonry construction on a building site. The major sources of error encountered during the automated masonry construction process as well as the required tolerances for the masonry process are described. Based on these considerations, two sensor strategies for positioning and orientating the robot are described in detail. An assessment of these strategies and a description of simulation results conclude this article.

1. INTRODUCTION

In the future, the production of residential buildings in Germany will be strongly influenced through the use of mobile bricklaying robots for use on the construction site. Fundamental concepts and enabling technologies for this type of robot as well as the prototype BRONCO have been presented by the authors in recent years [1 - 3].

One important issue for automated bricklaying within the building site environment is the assurance of positioning accuracy of the bricks. In this respect the bricklaying process can be divided into three processes:

(1) determination of the position and orientation of the mobile robot on the building storey,

(2) removal of a brick from a prepared pallet and calibration of its position with respect to the robots tool center point (TCP),

(3) placement of the brick in its correct position within the brickwork.

This paper classifies and systematically evaluates two feasible sensor strategies for the first of these three processes which fulfil the prerequisites of accuracy, robustness and economy. Section 2 describes the common sources of error that must be overcome by any sensor system for measurement of vehicle position and orientation. Section 3 describes the problem of position measurement, derives the coordinate systems of the robot and details two feasible measurement strategies. In Section 4 both a summary of further sources of error and quantitative evaluation of the two measurement concepts are discussed. Finally Section 5 concludes the paper with a summary of the two measurement principles.

2. CAUSES OF ERROR FOR AUTOMATED MASONRY CONSTRUCTION

The overall position accuracy for the process of automated masonry construction can be deteriorated by the following sources of error :

Robot - position, orientation and inclination errors with respect to the ground, internal inaccuracies such as axis position errors, finite joint stiffness and elastic bending.

Brick Pallets - position, orientation and inclination errors with respect to the ground.

Bricks - size differences due to production tolerances, position and orientation errors on the pallet caused by transport,

Masonry work - position, orientation, inclination and alignment errors in the existing masonry work.

In order to guarantee the necessary brick positioning accuracy the errors listed above must be automatically detected and compensated for. Apart from the robot internal inaccuracies all errors are caused by the local environment or human influence. Thus in addition to the internal robot sensors, the use of external sensor systems is indispensable if the external errors are to be overcome. The following sections describe and evaluate in detail two sensor systems which can be used to determine the robot position and orientation on the building storey.

3. DETERMINATION OF THE ROBOT POSITION AND ORIENTATION

3.1 PROBLEMS AND DEMANDS

To guarantee mechanical stability, the robot is propped up during the automated masonry process. Thus the robot has a temporarily stationary position from which the working envelope is limited by the reach of the manipulator. Concluding the completion of a wall segment the outriggers are retracted and the robot navigates automatically to the next work position. After extension of the props the new position and orientation of the robot on the building storey must be measured. The following requirements must be fulfilled by this measurement :

- The measurement can be carried out in a stationary position.
- A measurement accuracy is necessary (position: ± 2 cm, orientation: ±0.05°), thus allowing any additional sensors in the end effector to be kept as simple as possible.
- The position and orientation are to be measured in a world coordinate system.
- Fully automated measurement process.
- Any external support such as artificial landmarks should be kept as simple as possible.
- The robot position and orientation should be measurable from any point on the current building storey.

A weighted evaluation [2] based on the main criteria of accuracy, outdoor suitability, automation, necessary external support, cost and processing requirements was carried out. The majority of the well known concepts from the field of automated guided vehicles such as odometry, inertial systems or wire guidance systems are not feasible. Other methods such as video cameras or theodolites are either not robust or cost effective. However, two feasible concepts are currently being investigated:

- Absolute measurement utilising a rotating laser scanner and reflectors as artificial landmarks.
- Relative measurement by means of distance sensors mounted in the end-effector.

3.2 DEFINITION OF COORDINATE SYSTEMS

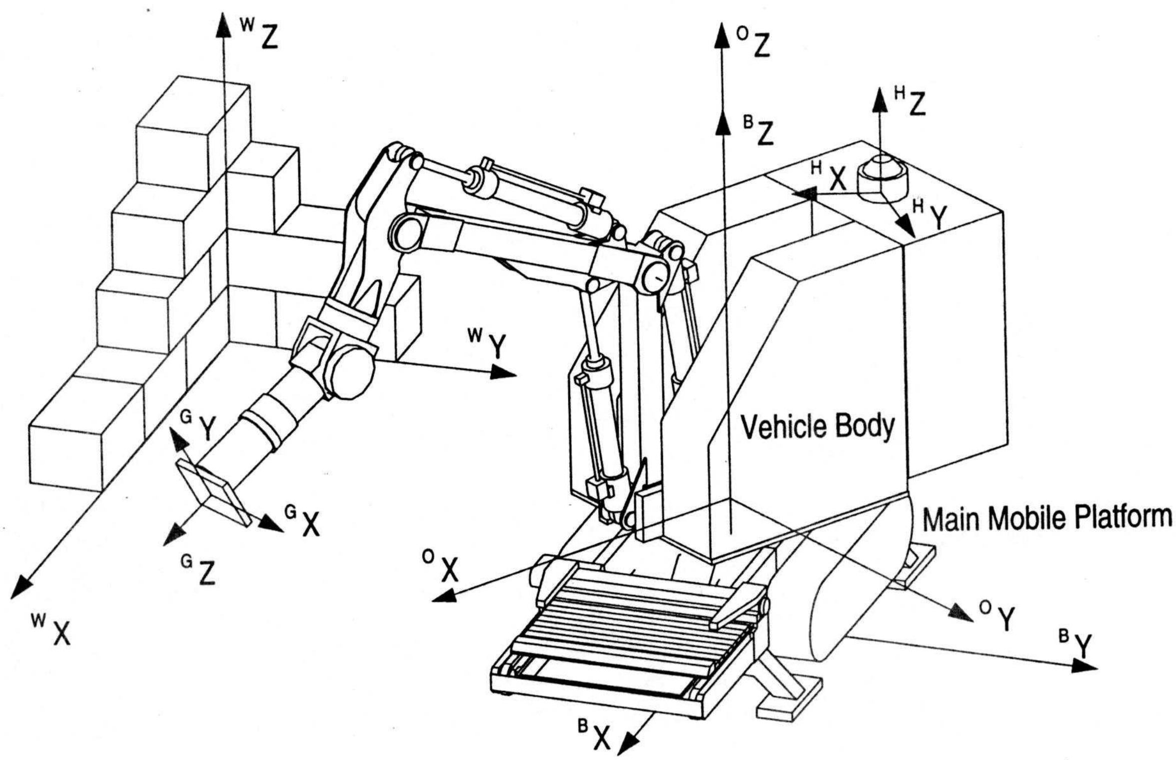

Figure 1: Coordinate systems for the mathematical description of the measurement strategies.

To facilitate a mathematical description of the measurement strategies the following coordinate systems were defined , see Figure 1:

${}^{W}x$ ${}^{W}y$ ${}^{W}z$	⇨	" *World Coordinate System* " Defined by an ideally flat building storey and a predefined corner of the ground plane.
${}^{B}x$ ${}^{B}y$ ${}^{B}z$	⇨	" *Main Mobile Platform Coordinate System*" Defined by the vehicle plane of the four outriggers and the main rotational axis of the robot.
${}^{O}x$ ${}^{O}y$ ${}^{O}z$	⇨	" *Vehicle Body Coordinate System* " Describes the orientation of the vehicle body to the chassis.

^Hx ^Hy ^Hz ⇨ " *Horizontal Laser Coordinate System*"
Defined by the vertical rotational axis of the laser scanner and the horizontal plane described by the rotating laser beam.

^Gx ^Gy ^Gz ⇨ " *End-effector Coordinate System* "
Defined by the geometric center of the suction plate.

Two measurement strategies are described in detail in the following sections. These concepts are described for the ideal case of a perfectly flat building storey. The case of a realistic building site with inclination errors and their compensation (which requires a three dimensional description) is not discussed due to space considerations. The reader is referred to [4] where this case is described in detail.

3.3 STRATEGY 1: ABSOLUTE MEASUREMENT USING A LASER SCANNER AND ARTIFICIAL LANDMARKS

The main principle of operation of laser scanner and artificial landmarks for the determination of absolute position is given in [5]. This measurement strategy can be used to determine the position and orientation of the mobile bricklaying robot. The laser is attached to the vehicle body and the reflectors are then erected on the building storey.

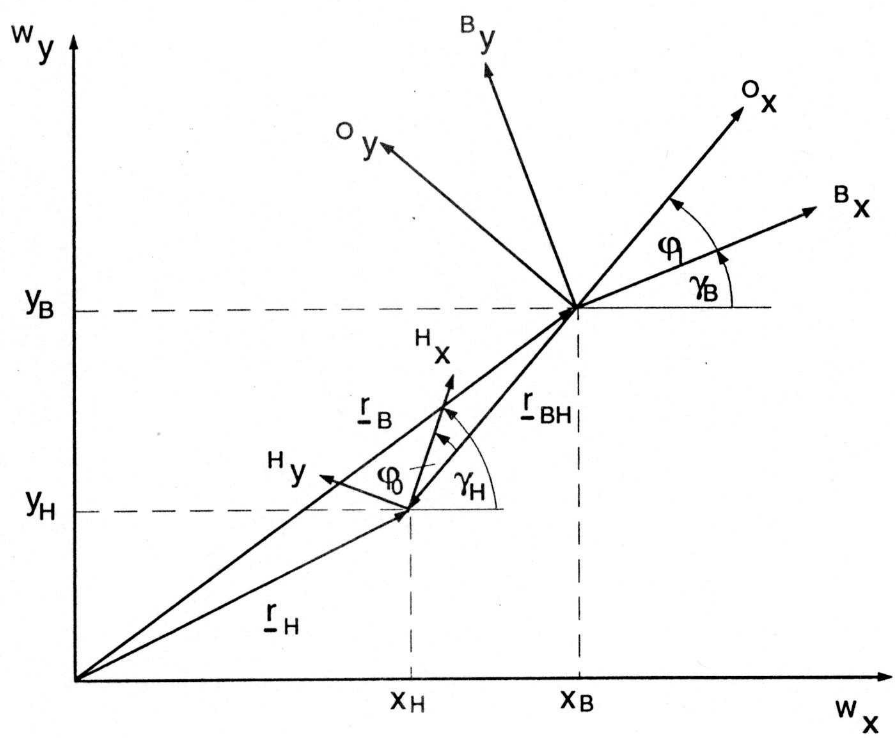

Figure 2: Determination of the position and orientation of the automated bricklaying robot using a laser scanner.

The initial variables are the position coordinates of the laser scanner x_H, y_H and γ_H in the world coordinate system ^WK and the rotational angle φ_1 of the main rotational axis in the main mobile platform coordinate system ^BK. If the angle between the main mobile platform coordinate system and the laser coordinate system is represented by φ_0, then equation 1 gives the orientation of the main mobile platform in the world coordinate system ^WK, see Figure 2.

$$\gamma_B = \gamma_H - \varphi_1 - \varphi_0 \tag{1}$$

The concept for calculation of x_B and y_B follows :

$$^W r_B = {^W r_H} - {^W r_{BH}} = {^W r_H} - {^{WB}T} \cdot {^{BO}T} \cdot {^O r_{BH}} = {^W r_H} - {^{WO}T} \cdot {^O r_{BH}} \tag{2}$$

Letting $^O r_{BH} = \begin{bmatrix} -L_H \\ 0 \end{bmatrix}$, the sensor data $^W r_H = \begin{bmatrix} x_H \\ y_H \end{bmatrix}$ and γ_H as well as

$$^{WO}T = \begin{bmatrix} \cos(\varphi_1 + \gamma_B) & -\sin(\varphi_1 + \gamma_B) \\ \sin(\varphi_1 + \gamma_B) & \cos(\varphi_1 + \gamma_B) \end{bmatrix} = \begin{bmatrix} \cos(\gamma_H - \varphi_0) & -\sin(\gamma_H - \varphi_0) \\ \sin(\gamma_H - \varphi_0) & \cos(\gamma_H - \varphi_0) \end{bmatrix}$$

Equation (3) is obtained:

$$x_B = x_H + L_H \cdot \cos(\gamma_H - \varphi_0) \tag{3a}$$
$$y_B = y_H + L_H \cdot \sin(\gamma_H - \varphi_0) \tag{3b}$$

When the position of the reflectors are known within a tolerance of ±1 cm (this is reasonable for a typical building site) then the absolute coordinates x_B, y_B and γ_B can be calculated with an accuracy of approximately 1-2 cm or 0,05 degrees respectively. This relatively high accuracy is offset by the relatively complicated on-site support needed for the positioning of the reflectors and the initial survey.

3.4 STRATEGY 2: DISTANCE MEASUREMENT RELATIVE TO THE FIRST ROW OF BRICKS

Instead of the absolute measurement system described in the previous section, this section describes a method which utilises common local environment characteristics to determine the position and orientation of the automated bricklaying robot.

A simple method is feasible when the first row of bricks has been manually laid and the end-effector possesses two distance sensors. Initially the end-effector is positioned so that it is exactly horizontal in the world coordinate system and the first row of bricks lies within the measurement range of both distance sensors. The distance between each sensor and the first row of bricks is then measured. Using the two distances a_1 and a_2 and a simple relationship [4] it is then possible to calculate the distance d_M and the orientation γ_M of the end-effector with respect to the first row of bricks (whose position in the world coordinate system is known), see Figure 3. Utilising the known geometric relationship between the end-effector and the mobile base, the exact position and orientation of the automated bricklaying robot can be determined.

A single measurement using this concept is not sufficient to facilitate calculation of the position of the robot along the wall. Thus a second measurement with respect to another wall is necessary if the coordinates x_B, y_B and γ_B are to be determined. It should be noted that the angle of orientation between the two reference lines of the walls should be $\delta \neq 180°$, see Figure 4.

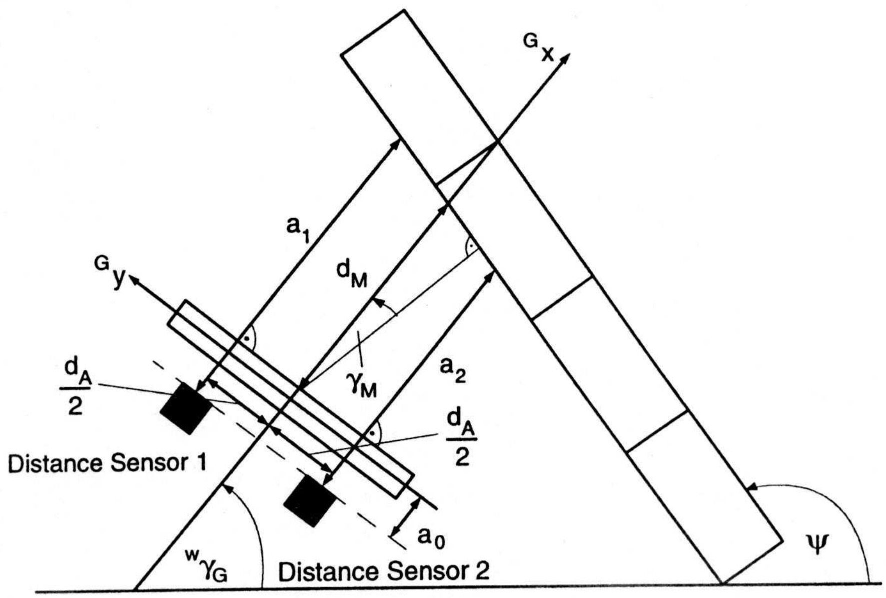

Figure 3: Determination of distance and orientation of the end-effector with respect to the first row of bricks.

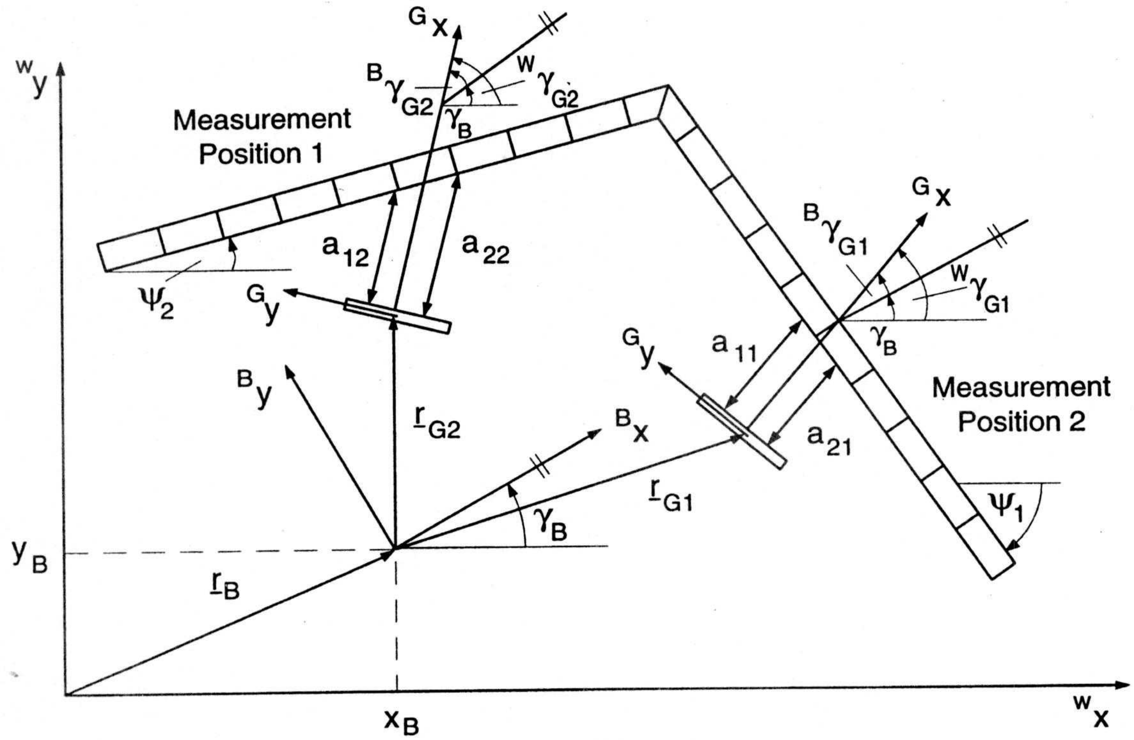

Figure 4: Determination of the position and orientation of the mobile robot by means of two distance measurements to the first row of bricks.

The overall accuracy of this method can be increased by performing several measurements and statistically evaluating their results. The main advantage of this process is the fact that the robot is able to measure its own position, thus eliminating the complicated positioning of reflectors needed in the absolute measurement strategy. Despite this advantage, this method can only be exploited in buildings where the first row of bricks have been laid and where this first row has a corner or bend.

4. ACHIEVABLE POSITION ACCURACY

The accuracy of both strategies for determination of the robots position and orientation is deteriorated by the following sources of error :

- Positioning errors in the installation of the reflectors.
- Inclination errors of the robot.
- Sensor measurement tolerances :
  - Inclination angle sensors
  - Laser scanner
  - Main rotational axis angle sensor
  - Distance sensors
- Errors in the first row of bricks
  - Orientation errors
  - Position errors
- Errors in the inverse kinematic transformation of the robot control system.

The attainable position and orientation accuracy of the measurement strategies presented in Sections 3.3 and 3.4 were simulated taking into account the error sources listed above. Figures 5 and 6 illustrate the simulation scenario used. The simulated errors, i.e. Δx_B, Δy_B and $\Delta \gamma_B$, between the actual (x_B, y_B and γ_B) and calculated position and orientation of the robot are given in Tables 1 and 2. The second column quantitatively describes the error source.

Strategy 1: Absolute measurement by means of a laser scanner and reflectors

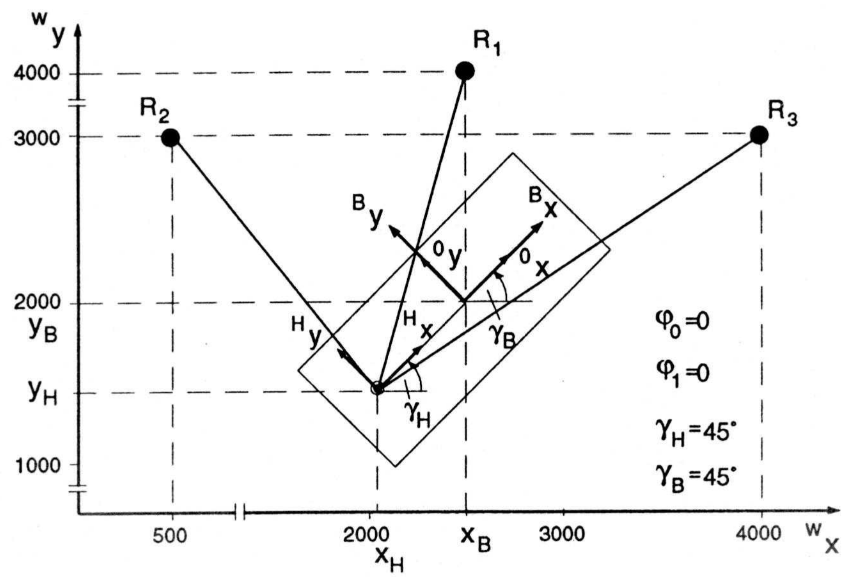

Figure 5: Simulations scenario for strategy 1 (semicircular arrangement of reflectors)

Error Source		Resulting Measurement Error		
Type	Value	Δx_B [mm]	Δx_B [mm]	$\Delta \gamma_B$ [Grad]
Position errors of the reflectors	±20 mm	16	14	0.22
Inclination error of the robot	+5°	180	5	0.03
Measurement errors :				
- Inclination sensors	0.1°	8	8	<0.01
- Laser scanner	±0.01°	0.06	0.06	0.01
- Main rotational axis sensor	±0.01°	0.06	0.06	0.01

Table 1: Error sources and their effects on the position and orientation accuracy of the automated masonry process.

Strategy 2: Relative measurement using distance sensors in the end-effector

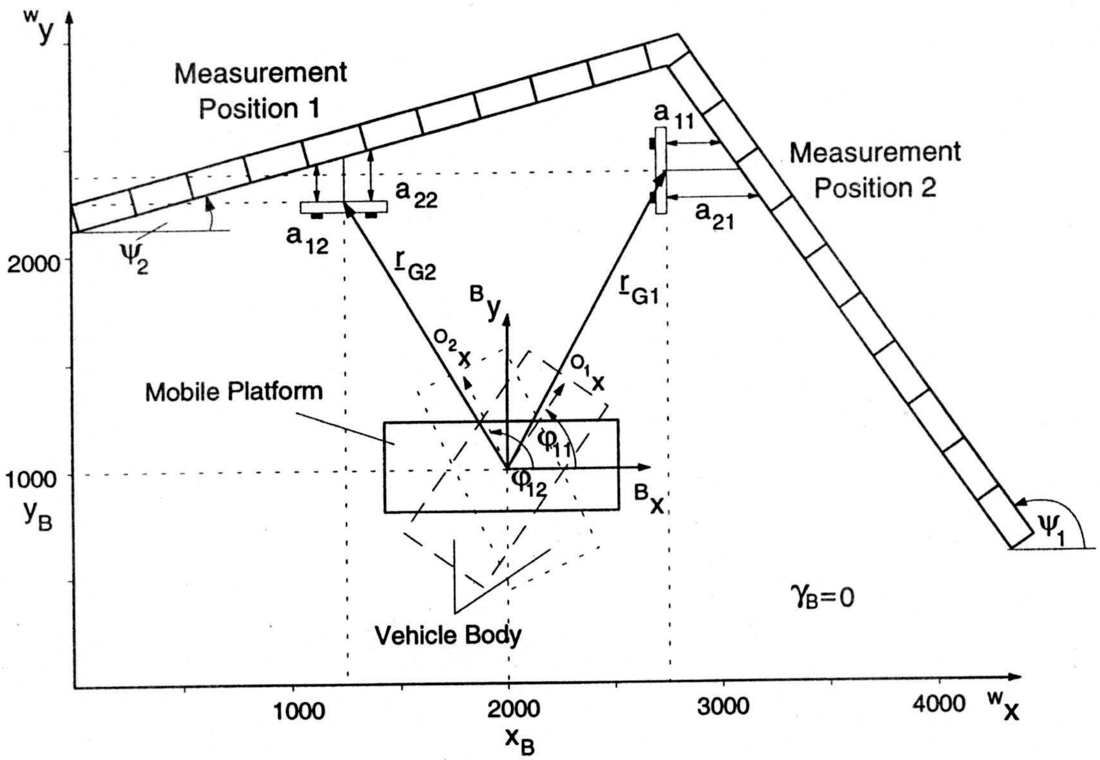

Figure 6: Simulation scenario for strategy 2.

Error Source		Resulting Measurement Error		
Type	Value	Δx_B [mm]	Δx_B [mm]	$\Delta \gamma_B$ [Grad]
Inclination error of the robot	+5°	7	8	0
Measurement errors : - Distance sensors	±2 mm	5	6	0.75
First row of bricks : - Position error - Orientation error	±20 mm ±2°	20 20	20 50	0 1
Internal robot errors : Inverse transformation error	±10 mm	15	3.5	0

Table 2: Error sources and their effects on the position and orientation accuracy of the automated masonry process.

5. CONCLUSION

The quantitative analysis of the two measurement strategies detailed in Tables 1 and 2 show that the following two error sources are the main contributors to measurement errors :

- Position error of the reflectors and inclination error of the robot in strategy 1.
- Orientation error of the first row of bricks and measurement error of the distance sensors in strategy 1.

The measurement errors of the other sensors e.g. inclination sensor, laser scanner and the measurement system of the first rotational axis, as well as errors of the inverse kinematic transformation are negligible.

Thus in order to achieve the highest possible level of position accuracy, the following measures must be adhered to :

(1) Accurate erection and measurement of the reflectors (± 10 mm).
(2) Measurement and compensation by means of the control system of the inclination error of the robot.
(3) Exact laying of the first row of bricks.
(4) Utilisation of high accuracy distance sensors.

Sensor strategy 1 offers the highest level of accuracy. Strategy 2 can also be used when the position and orientation errors of the first row of bricks are kept to minimum.

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