The Simulation and Modelling of Safety Systems for Construction Robots

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Abstract

In order for construction robots to become accepted on site it will be necessary for them to achieve demonstrable levels of operational safety at least equivalent to and probably higher than the equivalent manually operated system. In order to achieve the required levels of performance it will be necessary to provide sensor systems capable of detecting and responding to both static and dynamic obstacles within the system safety zones, this in turn requires an improved understanding of the relationship between the factors which influence the performance of the sensor system including location, coverage, scan rate and processing times. The paper therefore presents a simulation of the performance of a sensor based safety system for automated and robotic construction plant which can be used to support the design and validation of that system. Results of the simulation are presented in terms of system performance and, in particular, the failure to detect objects entering the safe zone of the system.

1 Introduction

An earlier paper [1] discussed the creation of a series of safety zones around a construction robot in order to ensure the safety of site personnel, of the machine itself and of the other machines and systems with which it must co-exist and collaborate and considered possible means for the monitoring of these zones. The identification of hazards and associated risk evaluation required to generate a conceptual design for a safety system is however only the first stage in the implementation of such a system. In practice, the achievement of a safety system which is both dependable and practicable relies on the provision of the necessary verification and validation features within the design and implementation process [2]. In particular, the designer must consider factors such as:

- The identification of blind spots.
- The identification of areas of sensor overlap.
- The effect of processing time on performance.
- The effect of the failure of an individual sensor on overall performance.
- The positioning of the individual sensors in relation to the robotic plant.

Safety verification and validation requires the designer to undertake a comprehensive examination of the designed safety system and its behaviour to establish deficiencies and errors. Essential to the verification and validation process are two major questions:

- How should the verification be carried out?
- Should the safety-related systems be verified discretely or continuously?

In response to the first question, verification is conventionally achieved by the use of modelling and simulation to increase understanding of system behaviour and to evaluate strategies for system operation [3]. In relation to the second point, continuous verification is a time-consuming and expensive process. However, discrete verification may well be insufficient for systems such as robots carrying out a series of sequential actions. For example, a robot autonomously carrying out a continuous series of actions under program control might give rise to hazardous situations at any point in the operating volume at any time in the motion sequence. The local sensor system must therefore be continuously active and hence the use of a discrete approach to verification may well create problems.

The construction of a physical model to directly demonstrate the performance of the designed safety system may well be expensive, time-consuming, impractical and even impossible [4]. As a result, such models tend to be not very accurate but have the

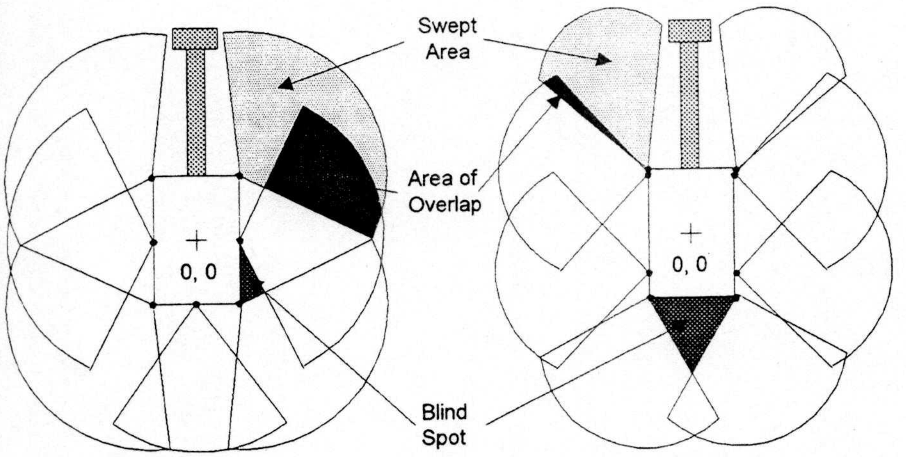
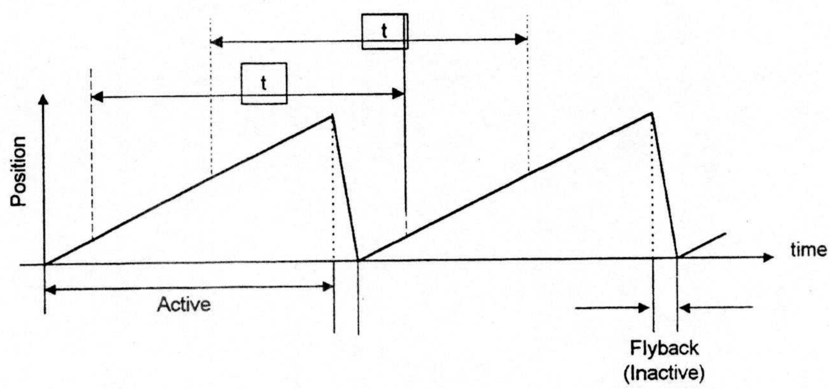
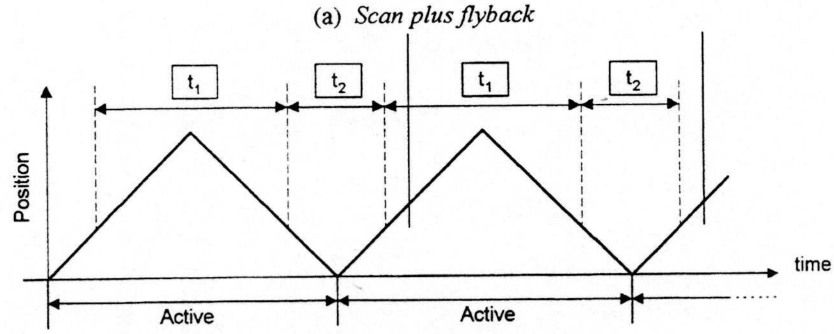


Figure 1: *Effect of sensor positioning on coverage including overlaps and blind spots*



(a) *Scan plus flyback*



(b) *Continuous scan*

Figure 2: *Scanning strategies*

advantage that they are easily understood and can isolate major features and problems.

By comparison, a computer graphics model can represent the operation and performance of the designed safety system authentically and accurately on the computer screen and graphical analysis is extremely useful as tool for exposing the behaviour of various system configurations. Both static and animated graphics are becoming more useful and important when real life experimentation would prove to be impossible, expensive, dangerous or time-consuming [5,6].

When a graphical model of a safety system is created, it can then be run in near real-time, which is of significant value in evaluating its performance [7]. With help of the simulation, the designer is able to study the behaviour of the safety system in relation to a wide range of possible hazard conditions. In addition, the simulation also aids in identifying systematic failures due to errors in the specification and hence in modifying the prototype safety system to achieve a near optimum sensor configuration.

The paper therefore considers the simulation of the operation of a sensor based safety system for a large mobile robot such as a robotic excavator and shows how even a relatively simple model of the sensor and its behaviour can provide a significant insight into the behaviour of the safety system and, in particular, into the operating time scales involved.

Results are presented which show how variations in sensor scan rate and processing time affect the ability of the sensor system to detect and respond to hazards in the form of dynamic obstacles within the safety zone of the excavator and consider how the safety system might be evolved to minimise the levels of associated risk.

2 Simulation and modelling of sensor behaviour for safety applications

The verification and validation of a safety related system is primarily concerned with establishing the performance and reliability of the designed system in respect of both predictable and unpredictable hazardous events and failures. The operation of the designed system may be directly related to the overall performance requirements of the robotic system as well as to known safety critical criteria. It is therefore important to make clear or prioritise any assertions used in monitoring before developing the strategy for verification.

Collision avoidance is a major safety function of the safety system for an automated and robotic excavator and the precision and efficiency of data collection and transmission are therefore of primary concern in establishing the reliability and accuracy the system. All assertions relating to the precision and efficiency of the sensing system will therefore be safety critical criteria. The contribution of the simulation to the verification of assertions will therefore cover the following features:

- The verification of the effect of the distribution of sensors on the surveillance area

For any individual sensor, the field of view is likely to be limited and a different distribution of sensors will create a different overall surveillance pattern. In addition, blind spots may well exist due to the incorrect distribution of sensors. During the simulation, the detection areas and coverage of the sensors is displayed on screen, enabling the evaluation of system behaviour with different distributions of sensors in order eliminate or minimise blind spots. Figure 1 shows the effect of altering the distribution of sensors on the overall coverage achieved and the associated regions of overlap together with any blind spots.

- The verification of the effect of the scanning period of the individual sensor on system reliability and performance

When sensors have an optimum distribution in relation to static obstacles, any failure to detect moving or dynamic obstacles is generally related to the scanning speed of the sensors. During the simulation, the behaviour of each sensor can be monitored in relation to random dynamic obstacles for different scanning rates. The threshold scanning speed for each sensor can thus be established in relation to the allowable conditions for a missed detection. In addition, the scanning method adopted can also influence the performance of the sensor system. Figure 2 shows the effect of two different approaches to scanning, scan plus flyback and continuous scan. In the first instance the time between scanning in a particular direction remains constant while in the second instance it varies between a short and a long interval.

- To evaluate the processing time required by the safety system.

The processing time of the sensor data is a further significant factor affecting the performance of the sensor. During the processing period, even if the sensor has an object in its field of view, detection will not be possible because the data cannot be accepted. This time interval is referred to as the *blind-time* of the sensor. The accuracy of the information provided by safety system is also closely related to the data processing time required because of the dynamic, real-time nature of its operation. By running the simulation model the influence of processing time on the detection failure rate and the accuracy of the information returned can be established. Thus, referring to figure 3, even though the sensor may scan the object when it is at position 1, the effect of the processing delay is that the object has reached position 2 by the time that processing is complete, indicating an object at position 1.

	Simulation Set 1	*Simulation Set 2*
Maximum sensing range	5 m	5 m
Minimum obstacle size	0.3 m	0.3 m
Obstacle speed	1 ms^{-1}	1 ms^{-1}
Minimum radius of danger zone	2 m	2 m
Initial position of object	5 m	2 m to 5 m at random
Scanning period of sensors	5s, 4s, 2s & 1s	2.5s, 2s, 1.5s & 1s
Data processing times	0.1s, 0.08s, 0.06s, 0.04s, 0.02s & 0.01s	0.03s, 0.025s, 0.02s, 0.015s & 0.01s

Table 1: *Conditions for simulation group*

- To evaluate the effect of sensor failure on performance.

During operation, the possibility of random failures resulting from the breakdown or failure of sensors must be considered and the subsequent effect on system performance evaluated. To ensure an acceptable level of safety integrity, the effect of the

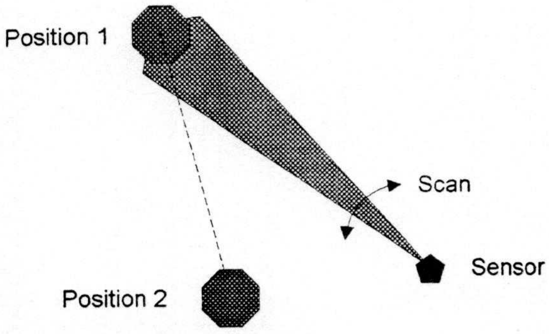


Figure 3: *Effect of processing delay on object detection*

failure of any individual sensor on the performance of the safety system must be examined. Using the simulation model the performance of the safety system when it contains one or several failed sensors can be evaluated.

3 Results

During the simulation, *failure* is defined as the likelihood that a dynamic random obstacle enters the danger zone of the protected system. These failures can result from three main causes as follows:

- A failure to detect the object.
- A system failure before detection.
- A system failure subsequent to detection.

The overall effect of this type of failure on system performance can be expressed in terms of the Composite Failure Rate (CF_{RATE}) which is defined in terms of the number of detection failures as:

$$CF_{RATE} = \frac{\text{Number of Failures}}{\text{Total Number of Obstacles}} \qquad 1$$

A *detection failure* means that the data is not acceptable even if the sensor successfully scans an obstacle. This may be because the data arrives too late to be of use, is unclear or the object is scanned during the blind time of the sensor. The occurrence of failures of this type can be expressed by the Detection Failure Rate (DF_{RATE}) which is expressed by the relationship of equation 2:

$$DF_{RATE} = \frac{\text{Number of Detection Failures}}{\text{Total Number of Scans}} \qquad 2$$

For the purpose of illustration, consider a scanning sensor mounted on top of the vehicle as in figure 4. The

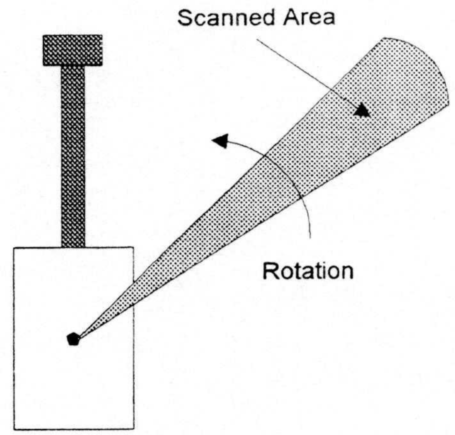


Figure 4: *Rotating scanner*

effect of varying both the scanning period and the processing time will in each case be evaluated over a total of 88 groups with each group representing a particular combination of processing time and scan rate. For each group there is a total of 10 simulation runs, each of which involves 100 random dynamic objects appearing in turn. The conditions for the simulations are given in table 1.

Referring to table 2, in the first simulation set the initial position of each random object is 5 metres from the vehicle and moving directly towards it; while in set 2 the initial position is varied between 2 m and 5 m. The highest failure rate over the 10 simulation runs is then taken as the result for that combination.

The results of the simulations are presented for each of the combinations of processing time and scanning rate in terms of the Composite Failure Rate and Detection Failure rate for different processing times (t_{PROC}) and scanning periods (t_{SCAN}) in Table 2.

From the results as presented it is seen that both the Composite Failure Rate and the Detection Failure Rate reduce as the data processing time is reduced. With the scanning period set at 5s or 4s the effect of reducing the processing time has less effect on CF_{RATE} than for lower scanning periods. However, reducing the scanning period results in a significant increase in the value of DF_{RATE} which reaches values of over 90% at the longer processing times in line with what might be expected.

Based on the results obtained from the simulations it was found that for objects less than 0.3 m in size the ration between t_{SCAN} and t_{PROC} was significant in determining performance. In particular, when t_{SCAN}/t_{PROC} is below 100, the value of DF_{RATE} was found to increase while no detection failures were found to occur in simulation set 1 when t_{SCAN}/t_{PROC} was set to be greater than or equal to 100.

4 Sensor modelling

The simulation as presented uses a simplistic model of the sensor and this would need further refining in order to provide additional data. This is particularly true in the case of ultrasonic sensing where the nature of the propagated wavefront and the sensor aperture may well have a significant influence on performance, particularly in the case of specula reflection.

For this reason, work is currently in progress to develop an improved model of an ultrasonic sensor which will allow for the proper evaluation of the effect of specula reflection and corners on the overall performance of the sensor system.

Other areas of development will include the introduction of the machine dynamics into the model in order to establish the effect of robot motion on the coverage and performance required. A particular concern here is the ability or otherwise of the machine to detect itself as a result of motion, a condition which could lead to a false output from the safety system.

5 Conclusions

The ability of a robotic item of construction plant to operate on site in co-operation and conjunction with humans and with other items of non-robotic plant is ultimately likely to depend upon the ability of the robotic plant to operate at a level of safety at least equal to and probably higher than that achieved by similar manually controlled and operated plant under the full range of conditions that might be expected on a construction site. In order to achieve this level of performance it is necessary to equip the plant with a sensor system capable of detecting and responding to dynamic and static objects within its safety zone. Indeed, it can be argued that the lack of any proven system of capable of providing this coverage is now the major limitation on the general deployment of automated and robotic construction plant.

On step towards achieving the general introduction of such plant is the achievement of a fuller understanding of the requirements of the sensor system necessary to create and monitor the safety zones around the plant and the entry of dynamic objects into those zones.

The paper therefore describes a form of simulation which can be used to evaluate the performance of such a sensor system in terms of factors such as position, scan rate and processing time and presents the results in the form of the Composite Failure Rate and the Detection Failure Rate for the simulations. From these results it can

	Scanning Period of Sensors(s)							
	Simulation Set 1							
	Composite Failure Rate				Detection Failure Rate			
Processing Time (s)	5s	4s	2s	1s	5s	4s	2s	1s
0.1s	55%	50%	65%	79%	18.18%	22.86%	72.31%	90.8%
0.08s	50%	40%	61%	80%	3.77%	17.8%	69.23%	91.86%
0.06s	47%	33%	30%	72%	0%	2.86%	39.83%	87.87%
0.04s	41%	31%	10%	44%	0%	0%	19.47%	73.73%
0.02s	40%	34%	0%	1%	0%	0%	0%	27.21%
0.01s	40%	34%	0%	0%	0%	0%	0%	0%
	Simulation Set 2							
Processing Time(s)	2.5s	2s	1.5s	1s	2.5s	2s	1.5s	1s
0.03s	39%	31%	16%	32%	0%	2.4%	19%	54%
0.025s	33%	25%	9%	24%	0%	0%	8%	41%
0.02s	30%	24%	8%	6%	0%	0%	9%	20%
0.015s	29%	25%	8%	1%	0%	0%	0%	5%
0.01s	35%	22%	11%	1%	0%	0%	0%	0%

Table 2: *System failure rates*

be seen that even a relatively simplistic model of the sensor system and its operation can be of significant benefit in establishing the operational limits for the sensor system and in determining the failure parameters for such a system.

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