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Stereovision Safety System for Identifying Workers' Presence: Results of Tests

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This article presents the results of extensive tests of a stereovision safety system performed using real and artificial images. A vision based protective device (VBPD) analyses images from 2 cameras to calculate the position of a worker and moving parts of a machine (e.g., an industrial robot's arm). Experiments show that the stereovision safety system works properly in real time even when subjected to rapid changes in illumination level. Experiments performed with a functional model of an industrial robot indicate that this safety system can be used to detect dangerous situations at workstations equipped with a robot, in human–robot co-operation. Computer-generated artificial images of a workplace simplify and accelerate testing procedures, and make it possible to compare the effectiveness of VBPDs and other protective devices at no additional cost.

human–machine interaction neural networks safety control
vision-based protective devices

1. INTRODUCTION

Flexibility in production is an important factor in industry. It is sometimes useful to allow a human and a machine (e.g., an industrial robot) to work together [1, 2] to optimize production. In a human–machine co-operation system, where the human and the machine share work space which cannot be separated, e.g., with fences, special safety systems are necessary. The distance between the human and the machine must be calculated quickly to account for their fast movement. When this distance is shorter than an acceptable minimum, the machine stops. More sophisticated safety systems consider information on the whole environment to avoid hazards or unnecessary downtimes (even if the distance between the human and the machine is short, the machine does not need to be stopped if it is moving away from the human) [6, 7, 8].

Vision based protective devices (VBPDs) are an example of safety systems for human–machine interactions. These devices are equipped with one or more video cameras. Since VBPDs have to work in real time, the algorithm used for image analysis cannot be time demanding. Image analysis can often be accelerated at the cost of accuracy. Fortunately, highly accurate detection of the position of the human (or the machine) is not necessary in this case, because the minimum safe distance between the human and the machine is relatively long (the process of stopping the robot's arm can take much more than 100 ms [8, 9]). The ability to work properly in different conditions is much more important. VBPDs must be robust against image distortions and interferences, which are likely to occur in a factory (e.g., noise, rapid changes in illumination level, shadows and fast moving objects). Section 2 will show that stereovision systems [10, 11, 12, 13]

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are robust against such image interferences. In the system this paper presents, an artificial cellular neural network (CNN) [14] is used for image analysis (for details on image processing, see Grabowski, Kosinski and Dźwiarek [15]).

2. METHODS

A stereovision safety system for identifying worker presence was tested using real and artificial images (for a discussion of virtual reality, see Zetu and Akgunduz [16]). To capture real images, the functional model of the safety system was equipped with two Scout scA780-54gc colour cameras with 54fps (Basler, Germany). Real images were used to investigate the robustness of the system against rapid changes in illumination level [17], the identification of the position of fast moving objects, the identification of the orientation of a bicolour marker, the size of the tolerance zone and the co-operation of a worker with a robot.

2.1. Functional Model of Vision Based Safety System

Initial tests were performed to investigate if the system could detect fast moving objects. Various floor textures, different types of objects (a cube, a cylinder and a sphere) and different colours (red, green and blue) were used. Each side of the cube was 6 cm long and the size of the other objects was similar.

The object was hanging on a very thin rope 1 m above the floor (the radius of the rope was much smaller than one pixel). The rope was dragged by a step motor with constant velocity of 2 m/s. Since one step of the motor corresponds to 1.2 cm, it is possible to calculate the distance covered by the object by counting the number of steps of the step motor. Figure 1 presents the displacement of an object calculated by the vision system (Δr_k) as a function of the displacement of the object calculated from the number of steps of the step motor (Δr_s). The results are in agreement, hence the vision based safety system can properly detect positions of fast moving objects, too.

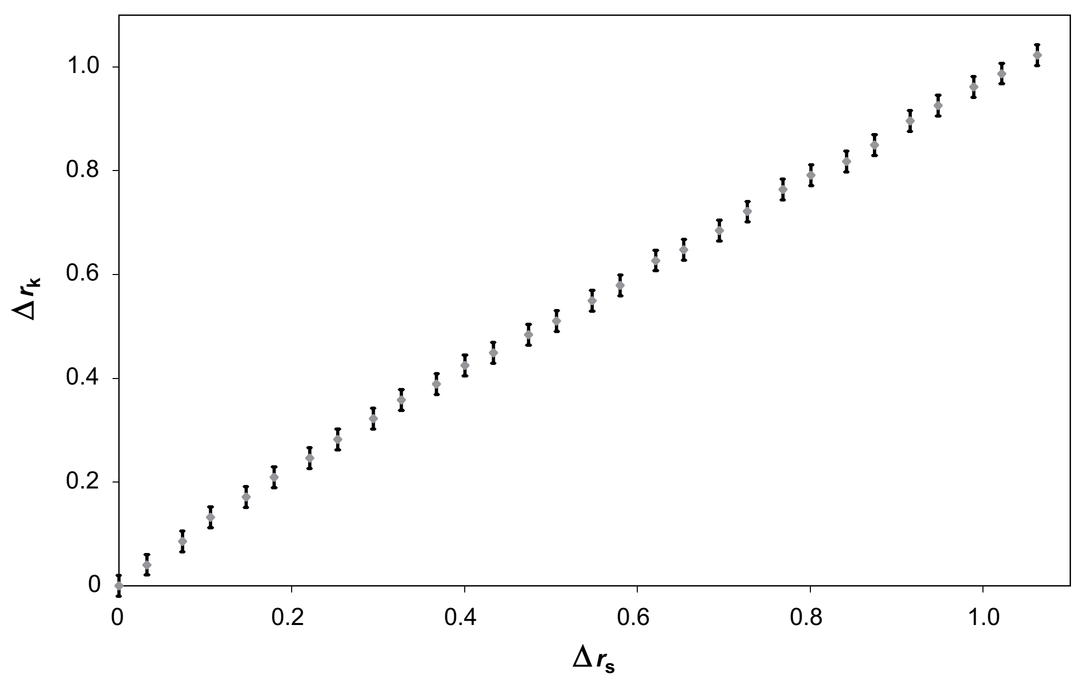

Figure 1. The displacement of the object calculated by the vision based safety system (Δr_k) as a function of the displacement of the object calculated from the number of steps of the step motor (Δr_s). *Notes*. The speed of the object: v = 2 m/s. The results are averaged over 100 tests.

The next step of the test involved investigating the robustness of the system against rapid changes in illumination level. Two sources of flashing light (2 × 2700 W) were used. Dashed lines in Figure 2 represent the average value of pixels <*V*> (0 = all pixels are black, 255 = all pixels are white) as a function of time. The value of <*V*> increases ~4 times during flashes.

Solid lines represent the position (in millimetres) of the object calculated by the vision system (the real position of the object does not change during this test). The the height of the object is also calculated by the system but is not shown in the figure. The average standard deviation of the position of the object for 10^4 measurements is under 1 cm, $\Delta r < 1$ cm. The results show that the system performs very well even when subjected to rapid changes in illumination level. The position of the object does not change significantly during flashes.

The system makes it possible to define the size and position of the detection zone (it is important to avoid accidents caused by incorrect operation of machine control systems [18]). However, the behaviour of the system is unpredictable on the border of the detection zone. The size of the tolerance zone, i.e., the size of the zone in which the probability that an object is detected by the system is over 10^{-3} and under $1–10^{-3}$, was investigated using an object which was slowly moved along the border with the help of step motors. One step of the motor corresponds to a linear displacement of the object of 0.9 mm.

For each position of the object, 10^4 measurements were performed and the number of cases when the system detected the object was recorded. Figure 3 shows the probability that the object will be detected as a function of the displacement of the object. Experiments show that the size of the tolerance zone is very small, ~2 cm. This value is much lower than for a typical detection zone.

This safety system was developed to make safe work in the proximity of a robot possible. Therefore, a simple robot with four degrees of freedom was constructed to perform additional tests (Figure 4 and AtomicWork [19]). The robot is powered by two step motors and two servomotors.

The main task of a vision based safety system is to stop the movement of a robot if the presence of a human is detected in the vicinity of the robot's arm (see Figure 5 and AtomicWork [20,

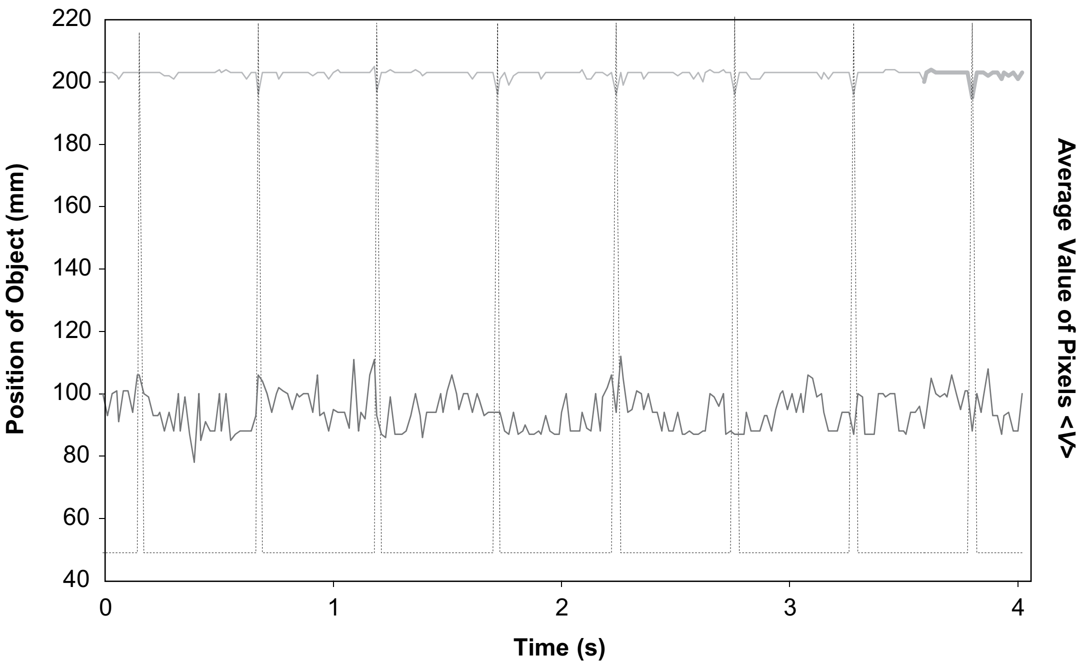

Figure 2. Average value of the pixels <*V*> (dashed line) and the position of the object (solid lines) as a function of time. *Notes.* Solid lines represent the position of the object calculated by the vision based safety system; bottom line = position on *x* axis, upper line = position on *z* axis.

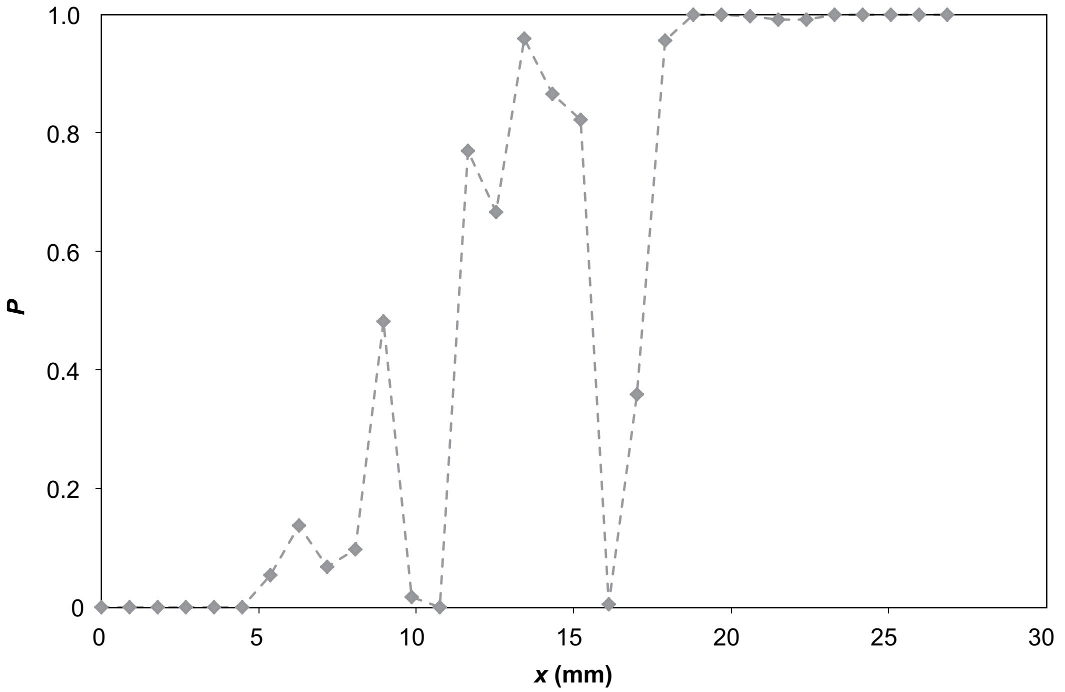

Figure 3. The probability *P* that the vision based safety system will detect an object as a function of the displacement of the object. *Notes.* Results for each point are averaged over 10^4 tests.

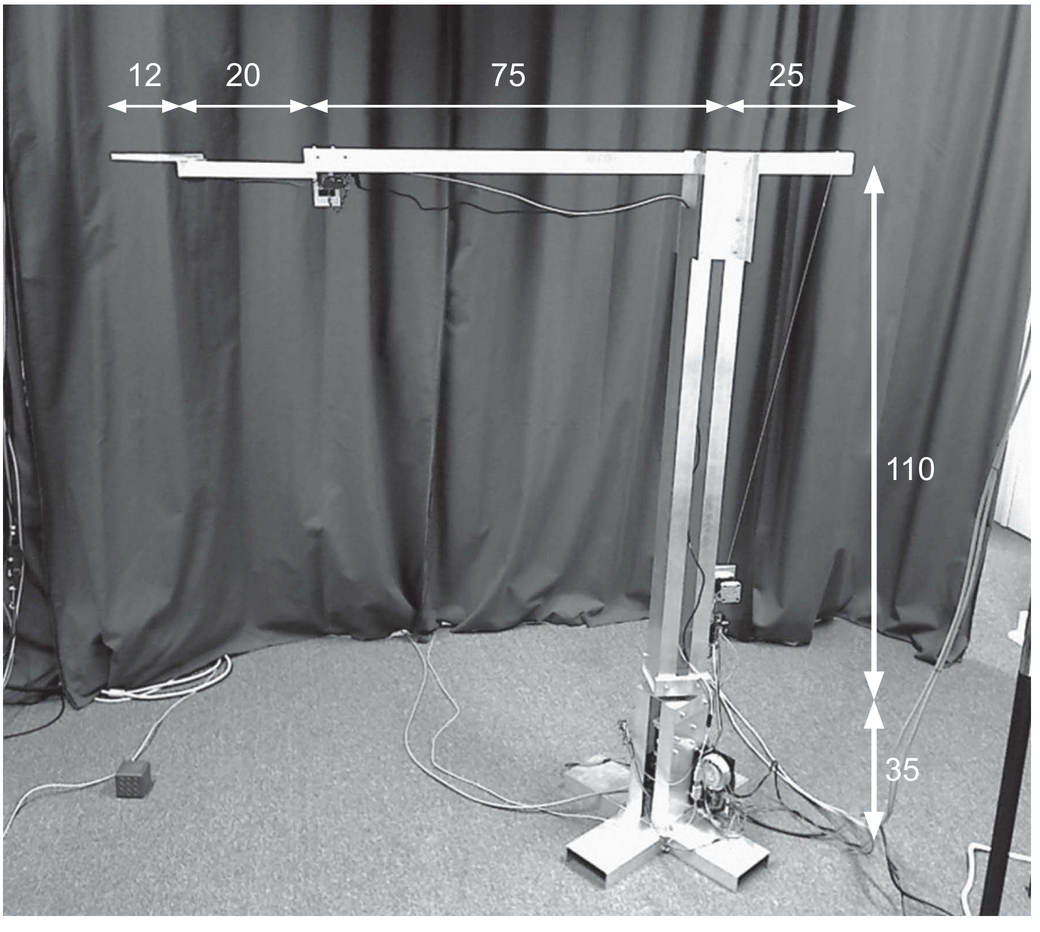

Figure 4. The height of the robot and the length of its arm (in centimetres).

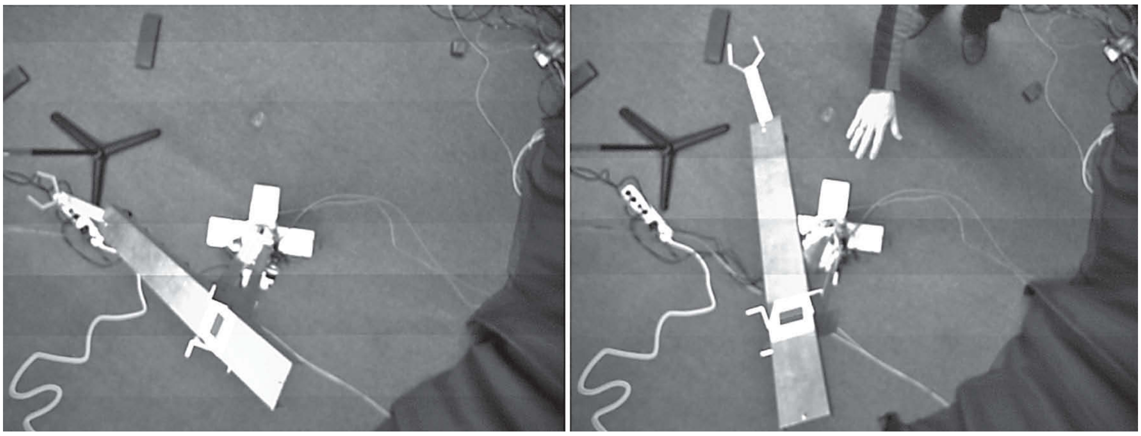

Figure 5. The vision based safety system stopped the robot's arm when it detected the presence of a human.

21]). To calculate the distance between a worker and moving parts of a machine, the position of the robot's arm should be known. To simplify the detection process and minimize the distortions of the image, the position of the arm is marked with a bicolour pattern placed near the axis. The marker consists of two parallel stripes: pure blue and pure red [15].

Next, 10^3 tests were conducted; in all cases the system stopped the robot's arm (for parts of the tests, see AtomicWork [20, 21]). The results of the tests show that the detection of dangerous situations at workstations equipped with a robot is a possible future application of the system, which has to meet all requirements listed in Standards No. ISO 10218-2:2011 [22] and IEC 61496-4:2007 [23].

2.2. Tests Based on Artificial Images

Testing procedures for VBPDs are very time consuming: tests must be performed for different types (e.g., finger, palm, arm or leg) and velocities of objects, different positions, different distance from cameras as well as different types of background and illumination level.

For this reason, it is preferable to use artificial images generated with virtual reality techniques. This significantly reduces the time necessary to carry out tests, as they are carried out automatically with a computer. It is important to note that not all tests can be carried out in this way (e.g., tests related to environmental factors like temperature or vibration). The ability to easily and cheaply test the operation of VBPDs through a computer model of a real workplace is an additional advantage of artificial images (Figure 6). Figure 6 presents two different human computer models, one of the workers is wearing a high visibility vest. The presence of a high visibility element (or lack thereof) does not influence the operation of VBPDs.

Grabowski et al. discuss a real assembly line from a factory in Poland, where a vision system may be useful [15]. It is long (30 m) and has nine production cells operated by two workers. The product from production cells is automatically carried away by a fast moving (~2 m/s) trolley. Products from all production cells are dropped in the same place. From time to time, a worker has to enter the area were the trolley operates. The worker passes through a light curtain which disables the trolley. Unlike a light curtain, VBPDs can take into account the position of the worker and the trolley to avoid unnecessary downtimes. Simulations show that the number of stops can be decreased to 31% and the total downtime to 16% when compared to values obtained for a light curtain. Such an increase in efficiency is possible because the trolley is inactive for shorter periods.

3. CONCLUSIONS

This paper presents the results of experiments conducted with real and artificial images. The safety system this paper presents operates efficiently in real time. It works properly for a wide

Figure 6. Virtual model of an actual assembly line used to test a vision based protective device (VBPD).

range of illumination levels and is robust against shadows and flashing lights. The system, which is based on CNNs, is able to calculate the object's position with high accuracy even in the case of fast moving objects ($v = 2$ m/s). The experiments show that the tolerance zone is relatively small; it is two orders of magnitude lower than the length of a typical robot's arm.

Modern production processes are increasingly flexible and this flexibility can be increased even further with VBPDs. VBPDs are especially useful in human–machine co-operation, e.g., when the operator co-operates with a welding robot or inserts components directly into the robot's gripper. At the same time, the operator has free access and a clear view of the production process because fences and barriers can be removed. Experiments conducted with a robot show that stereovision safety systems detect the presence of humans and properly identify the position of the moving robot's arm. Therefore, they can be used in human–machine co-operation.

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