Monitoring a Wide Manufacture Field Automatically by Multiple Sensors

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Abstract This research is dedicated to develop a safety measurement for human-machine cooperative system, in which the machine region and the human region cannot be separated due to the overlap and the movement both from human and from machines. Our proposal here is to automatically monitor the moving objects by image sensing/recognition method, such that the machine system can get enough information about the environment situation and about the production progress at any time, and therefore the machines can accordingly take some corresponding actions automatically to avoid hazard. For this purpose, two types of monitor systems are proposed. The first type is based on the omni directional vision sensor, and the second is based on the stereo vision sensor. Each type may be used alone or together with another type, depending on the safety system′s requirements and the specific situation of the manufacture field to be monitored. In this paper, the description about these two types are given, and as for the special application of these image sensors into safety control, the construction of a hierarchy safety system is proposed.

Key words Sensor network, robot vision, safety control, stereo vision, omni-direction vision

1 Introduction

In large-scale work fields in mechanic manufactures, the conventional safety countermeasure is separating the machine and the human region by fence and enclosure. However, in the case that workers have to enter the fence, such as in the case of trouble-shouting or maintenance, others may start the machine by mistake. This situation will be very dangerous. On the other hand, for easy design and for efficient production, new types of work environment called the human-machine cooperative system are introduced in recent factories. In such kind of new human-machine system in which mobile robots are used, the machine region and the human region cannot be separated[1], because the two region may often overlap due to the movement of human and the movement of machine (Fig. 1). To solve these problems, our proposal is to automatically monitor the moving objects by image sensing/recognition method, such that the machine system can get enough information about the environment situation and the production progress at any time, and therefore the machines can accordingly take some corresponding actions automatically to avoid hazard.

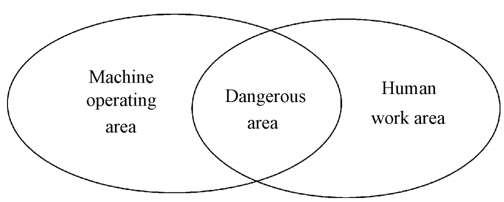

Fig. 1 The overlap area between human and machine is an unfixed area

Image sensing and recognition have been studied and applied for factory automation as an intelligent sensing method for many years. For instance, pattern matching method for 2D image, is very effective and widely used in quality inspection of production lines. The reason for this success is mainly because that the sensing objects are within the limited types, usually of known and fixed sizes and shapes. However, the sensing objects in case of the safety control in a wide work field, as we described in this paper, may be people and moving robots, are of more types and of various shapes, and the range of the sensing distance is also comparatively wide. As the sensing method for such kind of wide space, the advanced and complicated technology is desired, for instance, the omni-direction vision sensor and the stereo vision sensor which we will introduce in Section 2 and 3.

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Compared with the conventional sensing methods such as laser, super-sonic, and optical fence, relatively accuracy position and intelligent information are expectable by image sensing method. On the other hand, however, an image sensor sometimes may fail to detect an object because of the complexity of image sensing and recognition. Our solution here is to use multiple, different types of sensors, different image recognition algorithms, and furthermore to construct these sensors into a hierarchy sensor system. By the redundancy and the interpolation among the different types and among different algorithms of sensors, the hierarchy sensor system as a whole, is able to obtain enough information and to keep the reliability and correctness as well. In this paper, we describ two types of vision sensors to construct two types of monitor systems, one of them uses omni-directional vision sensors, and another uses stereo vision sensors. And as for the special and comprehensive application of these image sensors into safety control, the construction of a hierarchy safety system is proposed.

In the following, the description about the omni direction vision sensor and the monitor system based on it are described in Section 2, and the stereo vision sensor and the monitor system based on it are described in Section 3. Then the hierarchy sensing methods for safety control are discussed in Section 4.

2 Monitoring system using omni directional vision sensors

2.1 Omni directional vision sensors

Omni direction visual sensor (ODVS) is also called as omni direction camera. Fig. 2 shows the outlook of the omni direction camera and the photographs taken by it. An omni direction camera can cover a wide vision area as shown in the right side of Fig. 2. A cone shaped mirror is fixed at the upper side of the camera as shown in left side of Fig. 2, and it is structured in such a way that the scene which reflected on this mirror is captured by the CCD fixed at the lower part of the camera. If omni direction camera is fixed vertically on the floor, structures such as wall and door which stands, and human beings standing on the floor are seen located radically from the center of the circle in the image. In order to apply the traditional image processing method commonly used, it is necessary to convert conic project image into the evolved image as shown in Fig. 3 (a) and (b). In these evolved images, the image pixeles on the same column is the image on the same azimuth, and the columns from left to right shows the horizontal angle 0 degree to 360 degree.

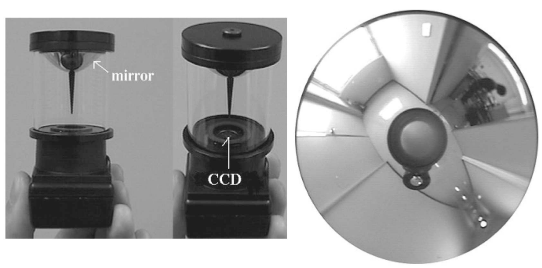
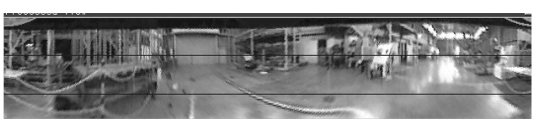


Fig. 2 The omni-direction vision sensor and the image it takes



(a) Evolved background image

(b) The evolved monitoring image including moving objects

(c) Difference image: (b)-(a)

(d) Azimuth zone corresponding to a moving object

Fig. 3 Detecting azimuth zone of moving object using an omni direction camera

2.2 Detecting presence area of moving objects using N-eye stereo vision

Fig. 3 shows the method for detecting azimuth zone of moving object by using one omni direction camera. At first, image of the monitoring area will be taken in advance, and the evolved image from it will be saved as a background reference image (Fig. 3 (a)) before starting the real time detection. After start the real time detection, the difference image (Fig. 3(c)) will be calculated, from the evolved monitoring image acquired in real-time (Fig. 3(b)) with the reference image (Fig. 3 (a)). In the difference image like Fig. 3(c), the neighbor columns which have the relatively larger numbers of non-zero pixels will be detected as the azimuth zone of a moving object (the white zone in Fig. 3(d)).

Although, one omni direction camera can detect only azimuths of moving objects, the area where the presence of moving object might be possible (from now onwards called as "presence area") can be detected with the N-eye stereo vision by using multiple omni direction cameras. Presence area is the area where all azimuth zones captured by omni direction cameras are overlapped as shown in Fig. 4. Mathematically it is defined below.

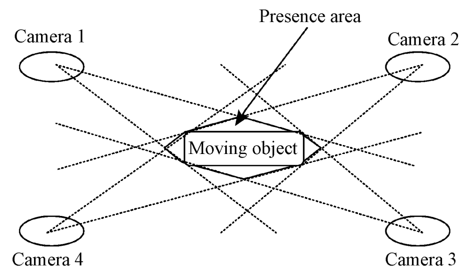


Fig. 4 The presence area of moving object

R_{ci} denotes the set of azimuth zones, which are detected by omni direction camera. Here "c" represents the number of omni direction cameras, and "i" represents the number of azimuth zone. For example, a set of azimuth zone of No. 1 omni direction camera is shown in (1).

$$R_{1i} = \{R_{11}, R_{12}, \cdots R_{1n}\} \quad (i \in I) \tag{1}$$

Here, the azimuth zone which is detected by one omni direction camera does not overlap. For No. 1 omni direction camera, the set is represented as shown in (2).

$$R_{11} \cap R_{12} \cap \cdots \cap R_{1n} = \Phi \tag{2}$$

When four omni direction cameras are used, the set of presence area, R_{pz} is defined as shown in equation (3).

$$R_{pz} = R_{1i} \cap R_{2j} \cap R_{3k} \cap R_{4l} (i, j, k, l \in I) \tag{3}$$

A wide area can be covered by using multiple omni direction cameras. In addition, observing the object at the same time by multiple cameras makes it possible to recognize objects much robustly, due to the use of redundant visual information[2].

2.3 Blockade space method for collision prediction

Collision judgment algorithm using the concept of the moveable blockade space will be used for collision prediction. Blockade space means the stop/braking distance layers which are formed by wrapping the presence area of the moving object[3]. Constitution of the blockade space is shown in the Fig. 5 (left).

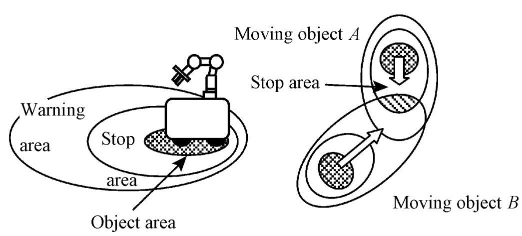


Fig. 5 Collision judgment based on the blockade space method

Blockade space is made up of 3 layers; the object area, the stop area and the warning/slow area. The object area here is the presence area shown in Fig. 4. The stop area is formed as an ellipse around the object area. Its longer axis is on the moving direction of the object, and the length of the axis is proportional to the moving speed. In other words, the length is the moving distance before the object can completely stop after an emergency braking was taken. The warning area is also an ellipse, including the stop area, and is to be used to take some earlier actions to assure safety. The axis direction of the warning area is the same with the stop area, and its length can be determined similar with the stop area. In addition, some factors on mechanical and control performance are also to be considered. In the above steps, the moving speed is estimated by measuring over a certain period the movement of the gravity point of the moving object.

Collision judgment is made by investigating the overlap of the blockade space. An investigation will be made about whether the blockade space for each moving object overlaps the one of the others as shown in the right side in Fig. 5. Then, if the moving object is a machine and it overlaps the slow area of other moving objects, the machine will be stopped by the stop area. Table.1 shows the overlap pattern given to decide the command to the machine. A stop command will be sent to the machine, except the overlap of slow areas.

Table 1 Collision prediction/prevention pattern

	Object area	Stop area	Warning area
Object area	Stop	Stop	Stop
Stop area	Stop	Stop	Stop
Warning area	Stop	Stop	Slow/Warning

2.4 Blockade space method for collision prediction

Here, an experiment of the application of collision prevention explained above is described. The configuration of experiment system is shown in Fig. 6. The system consists of four ODVSs, a four-screen unit, a PC server, a PC client, an autonomous guided vehicle (AGV), and an AGV controller (AGVC). The experiment is carried out by fixing a dummy in the monitoring area, and the AGV is allowed to run to 1m distance from the dummy. The position estimation algorithm for moving object is used[2]. The relation of AGV, the dummy and the running course is shown in Fig. 7.

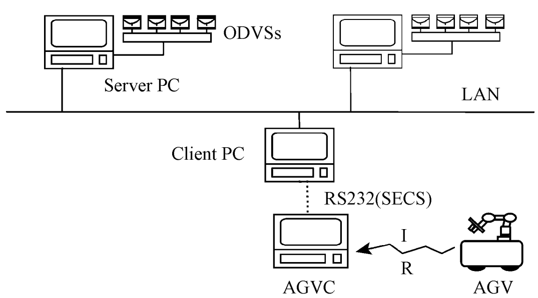


Fig. 6 Configuration of the experiment system

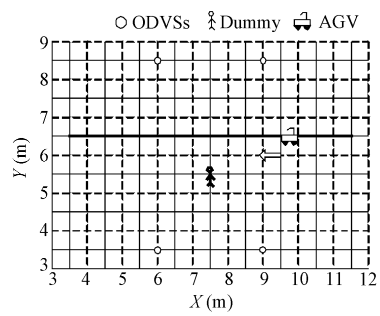
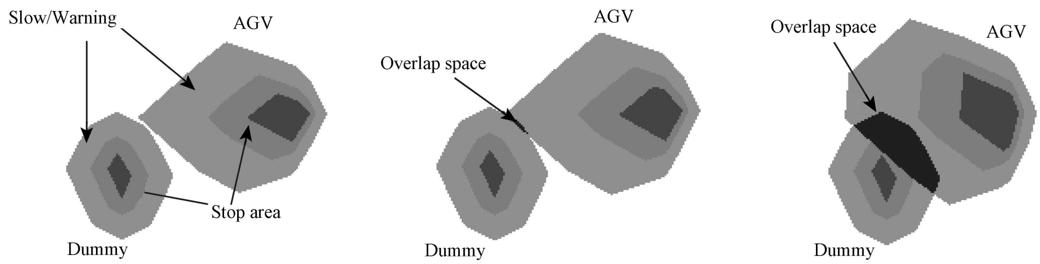


Fig. 7 The AGV route and the dummy position

Images of four omni direction cameras are collected as one video screen through the four-screen unit and it will be input into the PC server. By image processing, the PC server calculates the azimuth of the moving object taken by each omni direction sensor, and send the azimuth to the client PC. On the client PC, estimation of the position and prediction of the collision are implemented based on the azimuth information and the safety condition of the AGV will be decided. The safety-condition includes three conditions; safety (run admission), warning (slow), danger (stop). AGVC will make inquiry to the client PC about the safety-condition, and sends the result to the AGV.

Fig. 8 shows the result of the experiments carried out for collision prediction. The object at the right side is AGV, and the left side is a dummy people. In this figure, AGV moves straight to the left from the right, and the dummy people remains still. Shape of the presence area of the AGV changes with the movement of the AGV. This is due to change in the azimuth of the omni direction camera. On the other hand, the shape of the presence area corresponding to the dummy people dose not change.

In Fig. 8 (a), as the AGV and the dummy do not overlap their blockade spaces for each other, it is recognized as the safe condition, and AGV is allowed running. In Fig. 8 (b), a command for slowing down the speed will be sent to the AGV because the slow areas of AGV and dummy overlap.



(a) Safe condition (b) Slow/warning condition (c) Stop condition

Fig. 8 Result of the collision estimation

In Fig. 8 (c), the slow area of AGV is overlapped with the stop area of the dummy. Therefore, a stop command will be sent to the AGV in order to prevent the collision. Sometimes, the AGV and the dummy together are detected as a single object instead of two separate objects. Occlusion might be thought as the reason for it, and a solution on tracking function might be necessary. However in the experiment carried out here, the dependent area is judged as overlap pattern of collision according to Table 1, and a command for stop is sent to the AGV. Accordingly the AGV will stop, and therefore the safety control is assured even in this case.

As shown in this experiment, the monitoring system using omni-directional vision sensors (Fig. 6) can be used to avoid collision between mobile objects.

3 Monitor system by using stereo vision sensors

From the experiment described previously, we can see the above ODVS method is successful in collision prediction. However it is often required to know the size and approximate shape of the object being monitored. For example, in the safety control system, it is often necessary to know whether the object is a person or an AGV, then the control action will be different. The ODVS method is difficult to fulfill this task, since it use azimuth to detect objects, which results to relatively low accuracy in the position and in dimension of a detected object. To detect person and other moving object with 3D measurement, we develop another monitoring system based on stereo vision sensors which output disparity image.

3.1 Disparity image

A disparity image consists of pixels calculated according to the triangulation, the basic principle for stereo vision. The simplest explanation to stereo vision is for the case that two cameras with the same focal length are arranged on one image plane and have their optic axis parallel with each other. As shown in Fig. 9, if a point in the space is represented as $P(X, Y, Z)$ in world coordinate system, and its projection to the two images are (x_l,y_l) and (x_r,y_r), respectively, the following expressions are established.

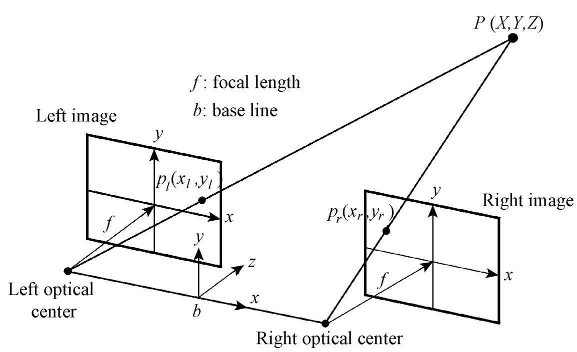


Fig. 9 Principle of stereovision

$$X = \frac{b(x_l + x_r)}{2d} \tag{4}$$

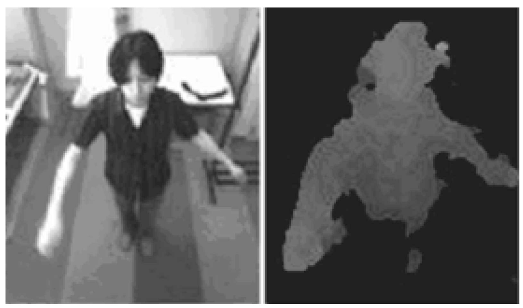
$$Y = \frac{b(y_l + y_r)}{2d} \tag{5}$$

$$Z = \frac{bf}{d} \tag{6}$$

Here, f is the focal length, b is the baseline, and d is the disparity

$$d = x_l - x_r \tag{7}$$

If f and b are already known, the 3D position in (X, Y, Z) can be calculated from their projection positions on the left image and the right image. Especially, the range Z can be calculated from disparity d alone. Fig. 10 is an example of disparity image. For the scene like in Fig. 10 (a), the pixels in the disparity image Fig. 10(b) is calculated according to expression (7).



(a) (b)

Fig. 10 Example of the disparity image

3.2 Segmentation of disparity image

In our study here, a stereo vision camera with relatively higher resolution (320×240) is used. Since it is not realistic to do the 3D conversion for all pixels in such resolution, the efficient technique for pixel classification, *i.e.*, the segmentation of disparity image is required. Although some related works were reported[4,5], they are for high-resolution aerial photo, unsuitable to the real-time processing related to safety control.

We implement the segmentation by combined use of the region-expanding step and the convex decomposition step. In the region-expanding step, among the neighbor pixels, the pixels having the near disparity value, *i.e.*, the disparity difference of pixels is less than a threshold, are classified into the same region. In the convex decomposition step, the regions obtained in region-expanding step are further split into convex regions, each of which usually corresponds to only one object. The details about segmentation method for disparity image can also be found in references[6].

3.3 3D measurement

After the disparity is segmented, the 3D measurements on objects are performed also by stereo vision in (4)∼(7). The results to be obtained in the 3D measurement are listed in Table 2, and the meanings of these results are explained in Fig. 11. The approach for 3D measurement is as the follows.

Table 2 Object list

Object No.	Object position x	y	z	Size dx	dy
···	···	···	···	···	···

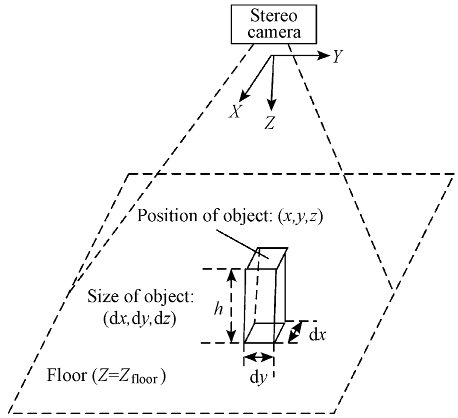


Fig. 11 3D measurement on the object

For each segmented region obtained in the previous step, coordinate (x, y, z) corresponding to the pixel at the 2D gravity center of the region is calculated, and is used as the gravity position of corresponding object.

Furthermore, $min\{x\}$, $max\{x\}$, $min\{y\}$, and $max\{y\}$ are calculated for all points (x, y, z) corresponding to the boundary pixels of each region, and the size, concretely the depth d_x and the width d_y, of the object corresponding to the region are calculated by $dx{=}max\{x\} - min\{x\}$ and $dy{=}max\{y\} - min\{y\}$. Finally, height $h = Z - Z_{floor}$, where Z_{floor} is the Z coordinate of floor in the camera coordinate system.

3.4 Monitoring system

Based on the stereo vision method described above, a monitoring system as shown in Fig. 12, is constructed, and an evaluation experiment is performed. The hardware and the software of the system are shown in the upper and low parts respectively in Fig. 12. As previously explained, here the monitoring system is mainly to be used to detect/count people and to measure their positions. In the hardware system, the entry/exit sensor is specially set up. This sensor is made up of short distance IC tag with which the peoples entering and leaving the monitoring area can be detected and counted. With this function of the system, miss-recognition or detection failure, caused by pattern recognition technique, can be improved. The part of human-body image detection consists of 4 stereo-vision nodes, each of which consists of a stereo-camera and a PC. Monitoring area of a node is basically independent of that of other node, and therefore it is possible to widen the monitoring area. In addition, by overlapping the monitoring area of each node, it is possible to improve the reliability and accuracy of the fusion information.

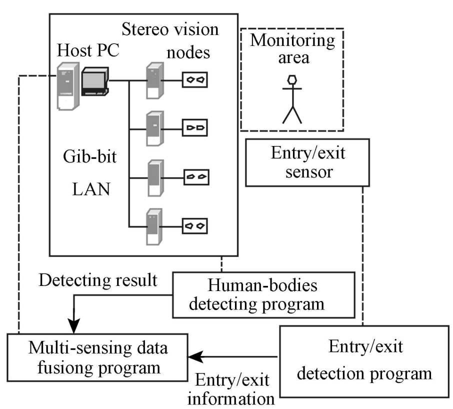
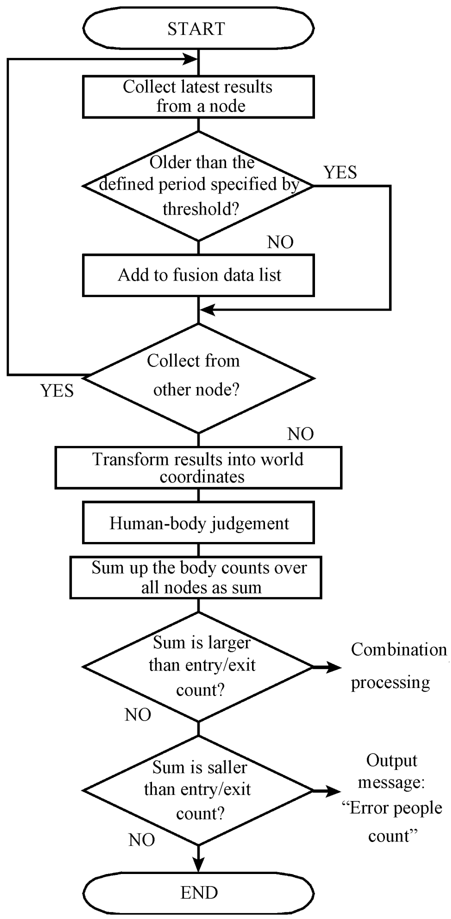
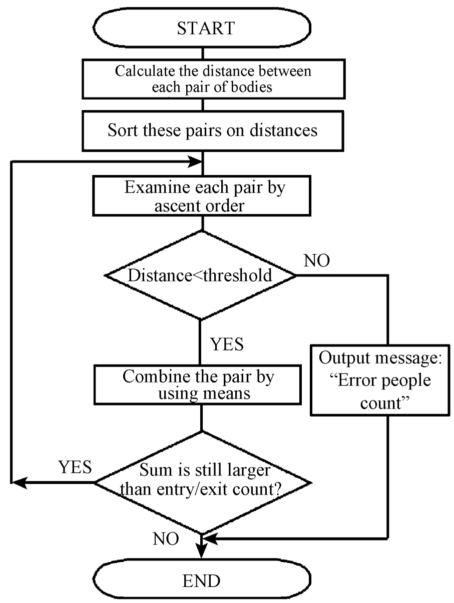


Fig. 12 Monitoring system using stereo vision camera

Before the execution of "Human-body detecting program" in Fig. 12, the disparity image of each monitoring area for each node is taken and is saved as reference image. During the execution of the program, if there is some change in difference of the disparity image of each node, detection, count and position measurement for human-body are performed. The information that is detected and measured by each node will be collected and combined by the host PC, and will be then verified with the count of people entering and exiting from the monitoring area, provided by the entry/exit sensor. This sensor fusion processing is shown in Fig. 13. If the verification is passed, the information of the position measurement will be output. If the verification is failed, the warning message “Error people count” will be issued.



(a) Collect results



(b) Combination processing

Fig. 13 Sensor fusion processing on host PC

3.5 Experiment and accuracy evaluation

An experiment for evaluating the accuracy is performed within an area of 4m×6m. Usually it is difficult to evaluate the performance for position measurement while tracking the object continuously in a relatively wide area. Here we use a method of examining the percentage of the measurement results which are on the scheduled route.

Considering two types of the status of people, as “still” and “walking”, various test patterns are used. Fig. 14 shows the examples of test patterns in which there are three persons. In detail, three persons are stand still in Fig. 14(a), but walk along some special routes in Fig. 14(b), (c), (d), and (e) respectively. As the example of the results from human-body detection and measurement, Fig. 15(a), (b), and (c) are corresponding to Fig. 14(b), (c), and (e) respectively. As shown in each case of Fig. 15, in more than 97% of the measurement results, differences between the measured and the actual walking route are within 30cm. We would say this result is good enough as the position measurement, since

30cm is smaller than average size of human body. As for about 2% of measurement results which are more than 30cm away from the scheduled walking route, the possible reason may be noise or some measurement errors.

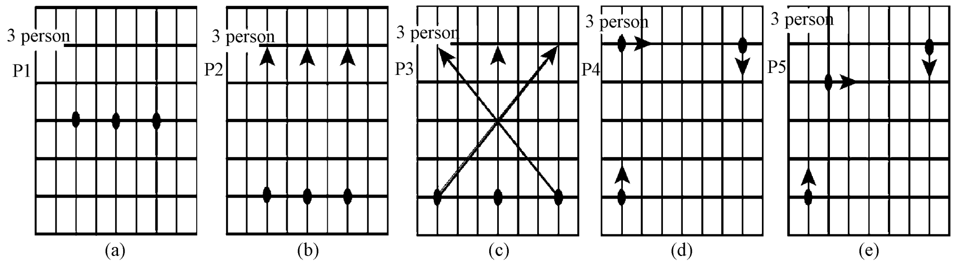
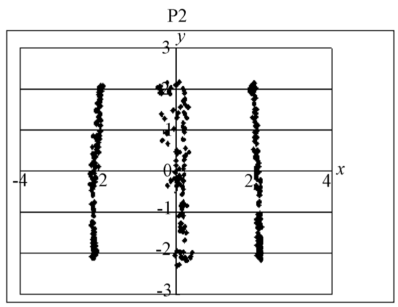
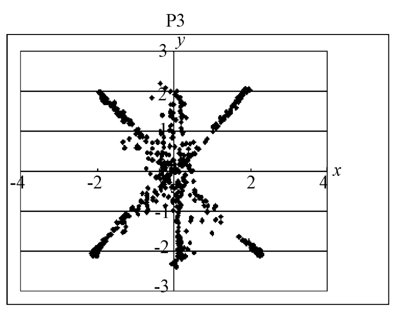


Fig. 14 Test patterns: examples of three persons



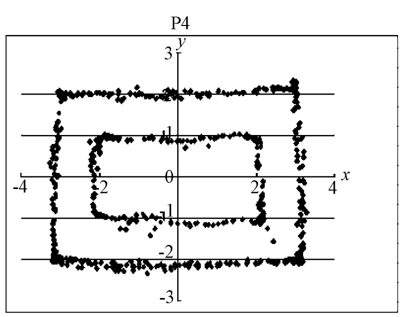
±cm	count	%
0	890	26.775
10	1895	57.01
20	394	11.853
30	91	2.7377
40	54	1.6245
50	0	0
60	0	0
70	0	0
80	0	0
90	0	0
100	0	0

(a) For the test pattern (b) in Fig. 14



±cm	count	%
0	1673	42.152
10	1383	34.845
20	677	17.057
30	145	3.6533
40	34	0.8566
50	57	1.4361
60	0	0
70	0	0
80	0	0
90	0	0
100	0	0

(b) For the test pattern (c) in Fig. 14



±cm	count	%
0	1623	39.779
10	1754	42.99
20	518	12.696
30	176	4.3137
40	9	0.2206
50	0	0
60	0	0
70	0	0
80	0	0
90	0	0
100	0	0

(c) For the test pattern (e) in Fig. 14

Fig. 15 Some experimental results for the test pattern in Fig. 14

The function of monitoring and measuring the human body with the above performance will be very useful to the safety control of avoiding collusion. However we will not rely on using the monitoring system describe here in this section alone to work in all cases for safety control, because there are 2% measurement results are relatively far away the route (>30cm) . As the sensing/monitoring system for safety control, there are also some other special requirements, which will be discussed in next section.

4 Construction of multiple sensor for safety control

Previously, in Section 2 and Section 3, we described two types of monitoring systems consist of two different types of image sensors. In this section, we compare their features and discuss the construction of using multiple sensors for the special requirement of safety control.

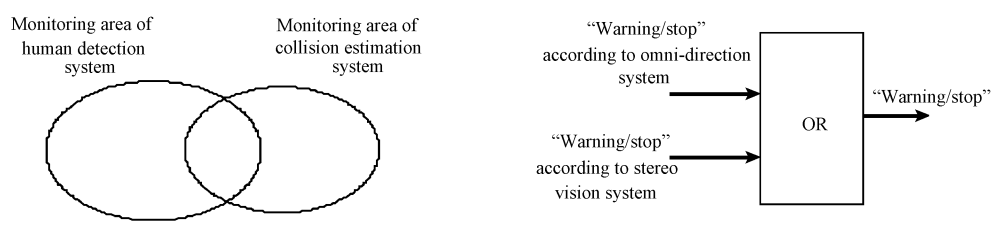
Table 3 compares the features of two monitoring systems using omni-direction camera and the stereo camera. As for the item "object extraction method", the stereo camera uses disparity image and the segmentation of it, and therefore is robust to the illumination change, as the result. The reason is that the disparity image is independent to illumination, as have explained in previous section. On the other hand, omni direction camera is "wide" in item "monitoring area", due to the use of cone shaped mirror (Section 2). However, as for the item "setting place", omni-direction camera is "stands on floor", therefore, may have the occlusion problem, *i.e.*, many objects is hidden by others in the front of camera. As the contrary, stereo camera can be "hang on ceiling", will have few problems concerning with occlusion.

Table 3 Feature comparison between the omni-direction camera and the stereo camera

	Omni-direction camera	Stereo camera
Object extraction method	Background difference	Stereo vision, segmentation of disparity image
Robustness for illumination change	Weak	Robust
Special purpose	Collision avoidance	Human-body detection
Setting place	Stands on floor (about 1m height)	Hang on ceiling (higher than 2.5m)
Monitoring area	Wide	Local

From the table, we can hardly say that the sensor of one type is absolutely better than the other. Therefore, if the cost is allowed, the two type sensors can be used simultaneously in one single system, compensating with each other.

As for how to construct a control system combining both these two type of sensors, a simple construction as in Fig. 16 may be considered. Fig. 16(a) shows the general relationship between the object area of these two different sensing system. The two monitored areas may be 1) overlapped, 2) the same area, and 3) independent, depending on the importance and the content of the object area. Fig. 16(b) is about how to combine the results of these two monitoring systems. Note that the two results are combined by the logic "OR". Even for the case that two type sensing are used to monitoring the same area and "AND" logic may be more reliable, "OR" logic here is safer than "AND" logic.



(a) Area relationship in a simple construction (b) Result combination in a simple construction

Fig. 16 Approaches for combining two types of sensors

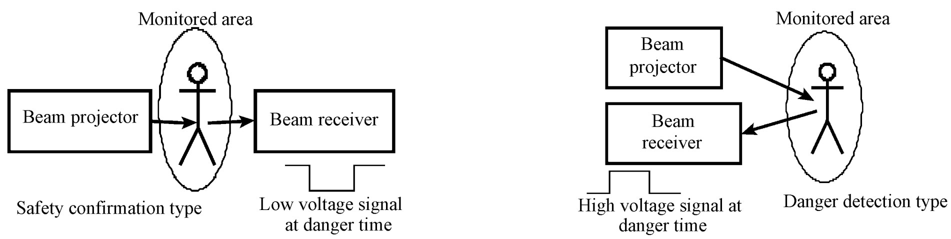
We may consider some sophisticated algorithm or device to combine the results from the two different types of sensors, instead of simply using "AND/OR" logic.

If the two types of sensor always output the same result, there are no difference in how to combine the results from these two types. The question is raised when the two types of outputs are different. Which one is correct? We may have some algorithm to evaluate their reliabilities and then chose the result with the higher reliability. In the application field of safety control, however, the most important matter is safety, *i.e.*, stop the machine at any possible or suspecious dangerous situation, even though the stop action may be judged according to an error result from sensors. This is why we simply use the OR logic to combine the results from the two different types of sensors.

4.1 Two different types of sensing for safety control

As discussed above, to some important area to be monitored without error, we can use multiple image sensing techniques, such as using two different monitoring systems for the same area in the same time. However, even such kind of multiple image sensing technique have rare examples in safety control[1]. The reason is simply that the image sensing system to detect moving object intruding the monitor area is "dangerous detective type". Since this type of system works by using high energy signal, when dangerous happens during the function fail, the high energy signal status for informing the dangerous will not be generated. This will be a serious problem for safety control[1].

On the other hand, the system that outputs the energy status only when the safety is confirmed is called "safety confirmation type". In other words, this type is the system enables the work of machine by sending/informing "safety" using high energy signal. The danger is informed by low energy signal. Therefore, failure is treated as danger, and therefore the safety is still assured even during the sensor failure, suppose that no dedicated energy is applied. Fig. 17 is an example of safety confirmation type and dangerous detection type for the case of optic line sensor.



(a) Safety confirmation by optical beam sensors (b) Danger detection by optical beam sensors

Fig. 17 Examples of two different types of sensing for safety control

4.2 Hierarch construction of multiple sensors for safety control

As far as the final judgment about safety is implemented by optic line sensor of safety confirmation type, and the information about the outside situation is always collected, the judgment of safety control can be done as the followings (see Fig. 18). 1) Safe (run continuous): when moving objects are outside at enough distance; 2) avoidance request to human, and/or also to machine in some case: when relatively nearer than 1); and 3) emergency shutdown (interlock): when further closed. As far as the interlock in the inside area works correctly, the outside of the hierarchy style safety equipment is not always the necessity of being a safety confirmation type, because the purpose of it is to reduce the stop rate as possible by preventing unconscious approaching the dangerous area.

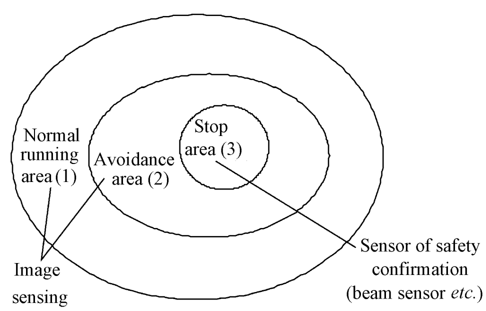


Fig. 18 Hierarchical Safety control

Considering the current level of the image sensing technology, such kind of hierarchy safety control is more realistic. Therefore, in our research here, image sensing technique for hierarchy safety control is focused, and the improvement in safety and reliability is attempted by the combined use of different types of sensors[7]. This is also the reason we construct two types of vision systems. Currently, the comprehensive system of combines these two types of vision systems is under construction, the result will be reported in other paper.

5 Concluding remarks

In a human-machine cooperative work system, the functions of preventing collisions has to be adopted. In order to implementing these functions, in this paper, two types of monitor systems were constructed. The first type is based on the omni -directional vision sensor, and the second is based on the stereo vision sensor. According to our experiment, both these two types usually work correctly and provide more accurate and more useful information than traditional sensors, such as laser, supersonic *etc*. However, absolutely no miss is not assured even with these two types, like other sensing methods. Consequently, the constructions for multiple sensors are proposed in Section 4 for the special requirements from safety control application. We believe that the hierarchy construction, among the others, is the realistic to satisfy the special requirement in the current technology level.

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