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COOPERATIVE INTEGRATION OF MULTIPLE STEREO ALGORITHMS

by

Masaki WATANABE
and
Yuichi OHTA

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INSTITUTE
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INFORMATION SCIENCES AND ELECTRONICS

UNIVERSITY OF TSUKUBA

Cooperative Integration of Multiple Stereo Algorithms

Masaki Watanabe and Yuichi Ohta

Institute of Information Sciences and Electronics
University of Tsukuba
Tsukuba, Ibaraki, 305, JAPAN

Abstract

In order to realize a flexible stereo vision system which can cope with a variety of scenes, we propose a new scheme to integrate multiple stereo algorithms in a cooperative framework. Each algorithm is implemented in a separate module and executed in parallel. The stereo correspondence obtained in each algorithm is stored in the module. Confidence of each stereo correspondence is evaluated based on the ambiguity in the search process and it is attached to the correspondence result. During the execution, each module communicates with other modules and offers subsets of its results to another by its request. The cooperation among the modules enables not only to improve the performance of each algorithm but also to make the integrated system highly adaptive to various scenes. A system integrating three stereo matching algorithms which use different kind of image features has been developed on a parallel computer to demonstrate the feasibility of our scheme.

1. Introduction

Stereo vision is a useful technique to passively obtain depth information. When a pair of feature points are identified on the right and left stereo images, we can determine its three dimensional location in the scene. A lot of stereo matching algorithms have been developed based on various kinds of features such as small area around a point, edge element, line segment, junction, and plane. When a stereo matching algorithm fits to an input scene, we can obtain rich and accurate depth information. We cannot expect, however, a single algorithm based on a single kind of image feature can cope with all scenes.

In order to realize a stereo matching system which can obtain rich depth information for a wide variety of scenes, it is essential to utilize multiple kinds of features in the system. A scheme so called sensor fusion is useful for that purpose. In sensor fusion, a scene is observed through multiple sensors and their outputs are fused into a single description. It was originally proposed to combine multiple physical sensors such as color TV camera, laser range finder, etc.[1] and was applied to combine the outputs of multiple virtual sensors. A virtual sensor means a vision algorithm which can extract three dimensional information from images. Moerdler and Kender[3] tried to combine multiple shape-from-texture algorithms in this scheme. The MIT Vision Machine[5] tries to fuse the output of various shape-from algorithms on the MRF. The scheme of sensor fusion, however, aims basically to combine only the outputs of sensors or algorithms. That is, every algorithm is executed independently with each other. This means no improvements can be expected in the output itself of each algorithm. It is necessary to supply the gain of an algorithm to another to improve the output of each algorithm.

One popular scheme to achieve such a relation between multiple algorithms is to connect them in cascade. The output of the preceding algorithm is supplied to the following algorithm and the latter is constrained by the former. Several stereo matching systems have been developed in this scheme[2][6]. In these systems, generally, the preceding algorithm deals with global features, such as planes or line segments, and the following one handles local features. The algorithm using local features is guided by the result using global ones to reduce the ambiguity in the stereo correspondence. This enables to improve the accuracy of matching as well as to obtain rich depth information based on multiple features. However, there exist obvious drawbacks coming from the fixed concatenation of algorithms. When the global feature cannot be extracted in a scene, or when the algorithm using global feature produces erroneous result, the following algorithm will be seriously affected. That is, it is very difficult to apply such a system to a variety of scenes. Furthermore, the flow of information among the algorithms should be bi-directional. The results obtained by using local features may be helpful to the global algorithm as well as the results by using global one is helpful to the local algorithm.

Ohta and Kanade[4] have developed an stereo matching algorithm which deals with two kinds of features simultaneously. In the algorithm, a stereo matching algorithm based on line segments and a stereo matching algorithm based on intervals on scanlines are integrated into a single framework of two-level dynamic programming. It enables to execute the two correspondence searches on the two features concurrently. The line segments supply inter-scanline constraints to the matching of intervals while the intervals supply intra-scanline constraints to the matching of line segments. Because there is no preference for the two features, the algorithm produces a reasonable matching result even when the line segments cannot be extracted on a scene. The search space for the integrated algorithm, however, is roughly the product of those of the individual algorithms and it is not feasible to simply extend the integration scheme to more than two features.

To overcome the difficulty described above, we propose a new scheme to integrate multiple stereo matching algorithms in a cooperative framework. In the scheme, each algorithm is implemented in a separate module and executed in parallel. During the execution, each module communicates with other modules and supplies subsets of its result to other modules when requested. In this sense, the multiple stereo algorithms are integrated cooperatively. The scheme is suitable to a parallel processing environment. A stereo matching system which integrates three algorithms based on three kinds of features has been developed on a parallel computer.

2. Issues on cooperative integration

We define a cooperative processing as a framework in which multiple modules perform their own tasks by supporting with each other toward a common target. Each module is created as a specialist of a particular stereo matching algorithm in our system. When a pair of stereo images are given to the integrated stereo system, every stereo algorithm starts its correspondence search in its own way. In case that an algorithm encounters a difficulty at a location in an image and which could be resolved by another algorithm, the algorithm asks for help to another one using an inter-process communication mechanism as illustrated in figure 1. If it cannot obtain a useful answer from other algorithms, it tries to decide the correspondence by itself. In sometimes, it postpones the decision to a later stage and tries to solve the correspondence again after other locations in the image have been processed.

As a consequence of the strategy described above, each algorithm first achieves the matching results at the locations where it does not need a help from other algorithms. In other words, when we look at a particular location on the stereo image, the order of algorithms applied to that location is determined adaptively to the situation in the image. This enables the integrated system to cope with a wide variety of stereo images. The total ability of the system is not at all a simple summation of that of the component algorithms as in the case of sensor fusion. Ability of each algorithm is improved through cooperation with other algorithms.

Figure 1 shows the internal structure of a module in our system. It is composed with three parts; the description of the algorithm, the rules for communication, and the results obtained by the algorithm. It should be noted that the results are not stored in a common database such as a blackboard but are distributed in each module. A major merit of this is that it can avoid to determine a common format to represent all the results obtained in the system. Determining a common format on a blackboard is not a simple task especially in an image understanding system. A small modification of the format will often cause the rebuilding of the entire system. Our solution for this problem is to store the results in each module which has created them. This enables the results can be efficiently represented in a most appropriate form. When an algorithm tries to see a result of another algorithm, it asks the algorithm instead of peeping the result directly. In other word, they communicate by using a common language not by sharing a common database. It is important that it is not necessary to prepare a single common language among all the algorithms. A common language is to be common at least only between the two algorithms which need communication.

The key concepts of the cooperative integration scheme described in this paper can be summarized as follows.

1) A stereo algorithm is implemented as an independent specialist.
2) There are multiple specialists in the system.
3) All specialists work in parallel.
4) Each specialist tries to solve the stereo correspondence problem in its own way.
5) A specialist may communicate with another specialist when he needs a help.

The scheme clearly has a nature of task parallelism and is suitable to be build on a parallel computer.

3. Overview of the integrated stereo matching system

Figure 2 shows the organization of the integrated stereo matching system we have developed. It has three stereo matching modules and a disparity map generation module to fuse the results obtained by the three modules. The four modules are activated in parallel and communicate with each other. Each stereo matching module starts its job by receiving a request from the disparity map module. Every time a new stereo correspondence is established in a matching module it is reported to the disparity map module. When a stereo matching module encounters a situation which needs a help by another module, it sends a query to the module. When and to whom to send a query is described as a set of if-then rules in each module. The module which received a query generates an answer and returns it to the sender. The actions which should be executed in a module by receiving a query are also described as if-then rules.

a) Point-based matching module

The point-based matching module obtains the correspondence of small areas on the right and left stereo images. It uses correlation to evaluate the matching and the area with a maximum correlation value is selected as the best match. It also employes a coarse-to-fine search technique to avoid the erroneous detection of local maxima. Though it is a classical stereo matching algorithm, it works well in a textural part. On the other hand, it will be confused in the area with smooth intensity or with repeated patterns. It will not also be able to detect an exact corresponding location when the appearances in the right and left patterns are distorted by some reasons such as occlusion.

b) Interval-based matching module

The interval-based matching algorithm obtains the correspondence between the intervals delimited by edges on the right and left scanlines. Scanlines are equivalent to epipolar lines on a rectified stereo image. The matching algorithm adopted here is exactly the same as the intra-scanline search algorithm described in Ohta and Kanade(). It searches an optimal set of correspondence on each scanline pair using dynamic programming. This enables to obtain a reliable matching result and to detect occluded portions referring to the context on a whole scanline. However the intra-scanline search alone does not use the inter-scanline consistency at all.

c) Segment-based matching module

A segment is a connected edge elements. The segment-based matching algorithm obtains the correspondence between the right and left segments. It evaluates the matching score based on the length and orientation of segments and the intensity values around them. Using segments as the units for correspondence search, it is possible to take the inter-scanline consistency into the matching result. A segment, however, is an image feature of relatively high level and might not be extracted enough on a stereo image. On the other hand, when a lot of segments are extracted, it becomes often difficult to determine the correct correspondence based on only the local properties of segments.

d) Disparity map generation module

Each stereo matching module can improve its own results in the cooperation with other modules. Because each module uses a different kind of image feature for the stereo correspondence, the results of the three modules are not always identical and they are stored in each module by a format specific to that module. When a particular feature does not extracted enough in a scene, the module based on that feature can only obtain a sparse depth information. The disparity map generation module gathers the results obtained in every matching module and compose them into a map. This map may be considered as an interface between a higher level module and the integrated stereo sensor system. We can expect that the map keeps rich depth information as far as at least a kind of image feature was extracted enough in a scene.

Although the concept of generating the map itself is basically the same as the sensor fusion, it should be noted that the fusion is performed on the fly. That is, whenever a new correspondence is obtained in a matching module, it is reported to the map generation module and the map is updated.

4. Cooperation among the stereo algorithms

The characteristics of the three stereo matching algorithms are summarized in table 1. It indicates that they are complementary to each other. The cooperation among the algorithms should be performed to make the best use of this complementary relation.

The point-based matching module first tries to obtain the correspondence at obvious edges. Then it tries to expand the search area around the edges as far as the matching does not become ambiguous. This enables to obtain the correspondence at textural area. In order to avoid the erroneous matching caused by occlusion, it asks that information to the interval-based matching module.

The interval-based matching module refers to the correspondence results in the segment-based matching module to keep the consistency in the vertical direction. Before starting the correspondence search for a pair of scanline, it asks the correspondence of segments which across the scanline. When correspondence of a certain segment is known, it limits the search plane for that scanline as illustrated in figure 3. The path determined by using dynamic programming is forced to go through the circle set around the position of the segment. The dotted polygon around the diagonal of the search plane shows the limited search space. The size of a circle is controlled based on the confidence of the correspondence of the segment. The results in the point-based matching module are also used to reduce the search space.

The segment-based matching module asks the interval-based module when the correspondence of a certain segment is ambiguous because of the existence of multiple similar candidates. The results in the interval-based module can supply the consistency in the horizontal direction and will be able to resolve the ambiguity. For the purpose, three scanlines across the segment are selected and the results on those scanlines are inquired. When an answer which supports a certain candidate is returned on a scanline, it increase the score of the candidate. In case that the three scanlines are not enough to resolve the ambiguity, another three are examined.

5. Evaluation and utilization of confidence values

5.1. Confidence value

When the information offered from a module is wrong, the module which asked and received the information will be misguided. Unfortunately it is almost impossible to classify the information to be correct or not for the module offered that information because it was generated somewhere in another module. We think the most appropriate one who can evaluate the quality of information is the one who has generated the information. That is, whenever a stereo matching module establishes a correspondence on a certain image feature, it should evaluate a confidence value for that correspondence and offer it to another module attaching with the information of correspondence. The module which received that information uses the confidence value to control the degree for taking the information into its own matching process.

5.2. Evaluation of confidence values

The confidence value for a correspondence is evaluated based on the ambiguity at the decision to make the correspondence. We think this will be reasonable because the reliability of a correspondence will be low when the best matching candidate is not obvious.

The ambiguity of correspondence is defined in each module based on its own criteria. This means the confidence values evaluated in each module do not always have a unified scale. We have no excellent solution for this problem at this point. In the current system, confidence values are defined in a heuristic manner in each module under a condition that every module should generate a confidence value with the [0,1] range.

In the point-based algorithm, the ambiguity of correspondence can be measured by the difference V_{dif} of the maximum correlation coefficient and the next maximum. The correspondence whose V_{dif} is less than a threshold k_1 is discarded as that the location is not appropriate for the point-based matching algorithm. The confidence value C_1 is defined as follows.

$$C_1 = 1 - \frac{\log V_{dif}}{\log k_1}$$

C_1 takes a maximum value 1 when V_{dif} is 1 (the best case), and takes a minimum value 0 when V_{dif} is equal to k_1 (the worst case).

The ambiguity in the interval-based matching algorithm is reflected to the cost of a path indicating the correspondence of a right and a left interval. Let V_{int} be the sum of the two cost values on both side of an edge, the confidence value C_2 for the correspondence at the edge is defined as the following.

$$C_2 = \exp(- k_2 \cdot V_{int})$$

Where k_2 is a positive constant. C_2 takes the maximum value 1 when V_{int} is 0, the best case. It decreases to 0 when V_{int} increases.

In the segment-based matching algorithm, each candidate for correspondence is given a score V_{seg} which accumulates the partial scores based on the similarity of the two segments and the information obtained from the interval-based module. When V_{seg} exceeds a threshold k_3, the candidate is adopted. The confidence value C_3 for that correspondence is evaluated as follows.

$$C_3 = \frac{V_{seg} - k_3}{V_{max} - k_3}$$

Here, V_{max} is an expected highest score. C_3 becomes 1 when V_{seg} is equal to V_{max} and becomes 0 when V_{seg} is equal to k_3.

5.3. Utilization of confidence values

When a module obtains information from another module, a confidence value for that information is attached. The module received the information controls the degree to rely on that information according to the confidence value.

As was described before, the point-based module refers to the occlusion information in the interval-based module and it does not try to obtain correspondence at such area. When the confidence value of that information is low, however, it tries the search anyway and gives a lower confidence value to the resultant correspondence as usual.

The interval-based module refers the correspondence so far obtained in other two modules. According to the confidence value attached to the information, it adjusts the size of the circle on the search plane as illustrated in figure 3. The circle is set smaller when the confidence value is higher. When there exist a discrepancy in the correspondence of the two modules, the one with higher confidence is adopted.

The segment-based algorithm refers the correspondence of edges on some scanlines obtained in the interval-based module. When it supports the correspondence of a certain segment pair, the score for the correspondence is increased. The amount is adjusted by the confidence value.

In the disparity map generation module, the confidence value is used to control the fusing process. The basic idea to fuse the three disparity values of the three algorithms is simply to take a weighted average of the disparities by using the confidence values. However, because the three matching algorithm use different kind of image features, the locations on the image where the correspondence obtained in each algorithm do not necessarily coincide with each other even when they originate from a common scene feature. Then, the disparity value obtained at a location is extrapolated around that point within a small distance on the map.

The confidence value in the extrapolated area is set as linearly decreasing with the distance from the center. After that, at each pixel on the map, the disparity value D and the confidence value C are calculated as the followings.

$$D = \frac{\sum_{i=1}^{n} D_i C_i}{\sum_{i=1}^{n} C_i}, \qquad C = \frac{1}{n}\sum_{i=1}^{n} C_i$$

Here, n is the number of results fused at the pixel position. D_i and C_i are the disparity and its confidence value obtained by the i-th correspondence. In case that the D_is have large discrepancy with each other, the results with lower confidence are removed from the averaging operation.

6. Implementation and experimental results

6.1. A mechanism for inter-module communication

An experimental system has been developed on a parallel computer Sequent-S81 with 8 processors. The S81 has an architecture of multiple processors sharing the whole memory. This is convenient for our application in which an input stereo image should be shared by multiple stereo matching algorithms.

Each algorithm is implemented in a separate module in our system. Every module is executed as parallel processes on the DYNIX operating system of S81. We have realized an inter-module communication mechanism based on message passing. The detail will be described elsewhere[7].

Figure 4 illustrates the behavior of a module from the view point of inter-module communication.
(a) When a module is activated, it has only a single process called accepter which is always listening to the call from other modules.
(b) When a query comes from outside, the accepter forks another process called replier which performs some real job necessary to return a reply for the query.

(c)(d) When the replier completed its job, the process is terminated.
During the execution of a job, the replier may send some query to other modules.

When a set of stereo images is given to the system, at least one replier is generated in each stereo matching module by the query from the disparity map module to perform the correspondence search for the whole image based on its specific algorithm. On the arrival of a query from other module, a new replier is generated to process it. All the repliers existing in a module at a time are executed as parallel processes. Of course the repliers in a module share the matching results so far obtained in that module. It is also possible to generate at the beginning more than one replier each of which share a part of task on correspondence search for the whole image. This enables to utilize the data parallelism contained in each stereo matching task.

Figure 5 illustrates the traces of communication among the modules. The horizontal axis indicates the time. The vertical axis shows the number of corresponding stereo pairs offered as the replies by using the inter-module communication. Figure 5 (a) is a trace for the block scene shown in figure 6 and (b) is that for the room scene in figure 7. It will be obvious that the communication among modules is controlled adaptively to the situation of the input stereo image. The room scene in figure 7 includes a lot of vertical segments closely located. This causes an ambiguity in the segment-based algorithm and increases the communication between the segment-based and the interval-based modules.

6.2. Experiments with various stereo images

Figures 6 through 8 shows three stereo images used for the experiment. The edge elements and edge segments extracted on each of the left image are shown in figures 9 through 11. Figure 6 is a scene of relatively simple toy blocks and has many characteristic edge segments. Figure 7 is a room scene having a lot of similar vertical segments. It also contains an occluded area where the boxes on the floor hide the door behind. Figure 8 is a scene of a car component. A lot of noisy edge elements are extracted at the surface texture and a few obvious segments are obtained.

The integrated stereo matching system has been applied to these stereo images under an exactly same condition; no parameters are manually adjusted to tune the system for a particular stereo image.

(a) Effects of cooperative communication

Table 2 illustrates the error rate of the correspondence obtained in each algorithm. We have prepared a set of correct correspondence for each stereo image to examine the error rate. Each column of the table show the false positive rate and the false negative rate for a stereo matching algorithm. Each row shows the rates for each stereo image in the two cases of with/without cooperative communication.

The false positive rates of the interval-based algorithm and the segment-based algorithm were clearly improved in all scenes under the cooperative processing. This indicates that the evaluation and the utilization of confidence in each algorithm is reasonable. It also indicates that the two algorithms are mutually improved by means of a bi-directional communication.

The false positive rate of the point-based algorithm was slightly improved in the room scene. This comes from the utilization of occlusion information offered by the interval-based algorithm. It contributes only a little to the rate, however, because the area of occlusion is fairly small. Other two scenes do not have obvious occlusion.

The false negative rate is also improved under the cooperative processing. This is because the ambiguity of correspondence in each algorithm was reduced by the help offered from other algorithms. A slight increase of the rate of the point-based algorithm in the room scene is a side effect of the avoidance of occlusion.

(b) Disparity map

Figures 12 through 14 shows the disparity map and the map of confidence value for each scene obtained as the output of the disparity map generation module. On the disparity map, the intensity scale is coded as the closer point to be the darker. The confidence value is coded as the higher to be the darker. The disparity map shows the disparity values extrapolated around the locations where the correspondence was obtained. On the map of confidence value, the area with low confidence means the disparity values in that area may be inaccurate.

The figures shows that the integrated stereo matching system can obtain rich depth information for a variety of scenes.

7. Conclusion

We proposed a new scheme to integrate multiple stereo matching algorithms in a cooperative manner. An experimental system integrating three stereo algorithms has been developed on a parallel computer. The cooperative processing is effective to improve the matching accuracy in each algorithm and the integrated system can cope with a variety of scenes. The scheme is suitable to be executed in a parallel processing environment.

We think the cooperative integration scheme is quite effective to build a computer vision system which integrates various shape-from algorithms in a unified framework. The cooperative integration in a parallel processing environment will be the key technique to realize a feasible vision system.

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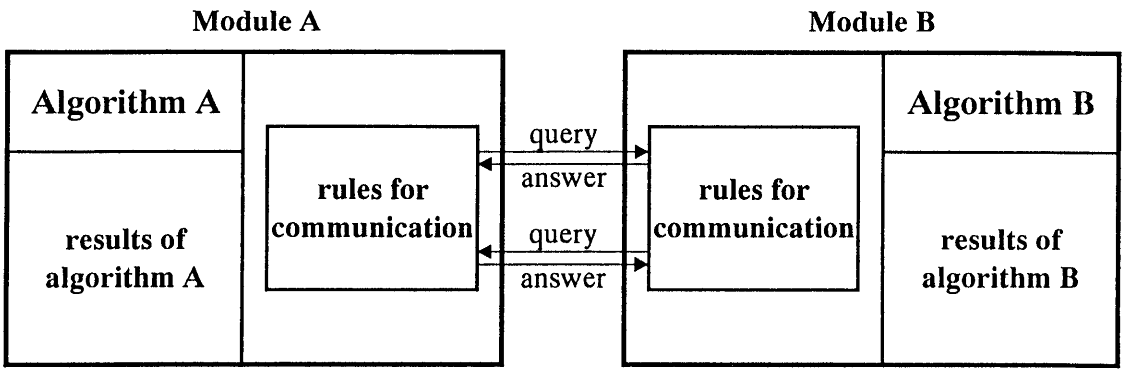


Fig. 1 Cooperative processing of multiple algorithms.

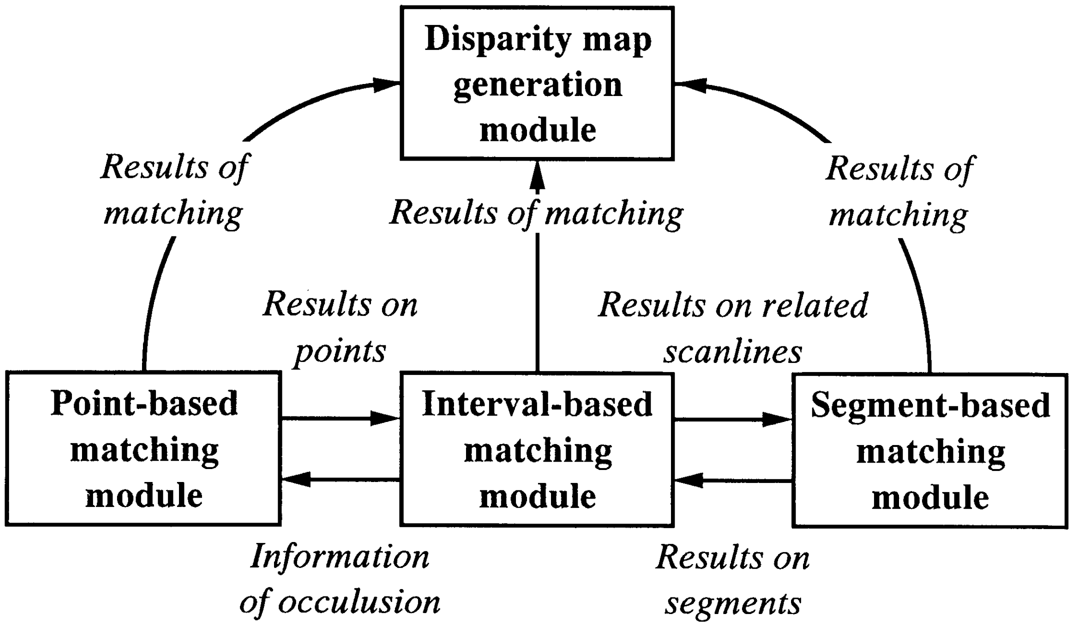


Fig. 2 Module organization in the integrated stereo matching system.

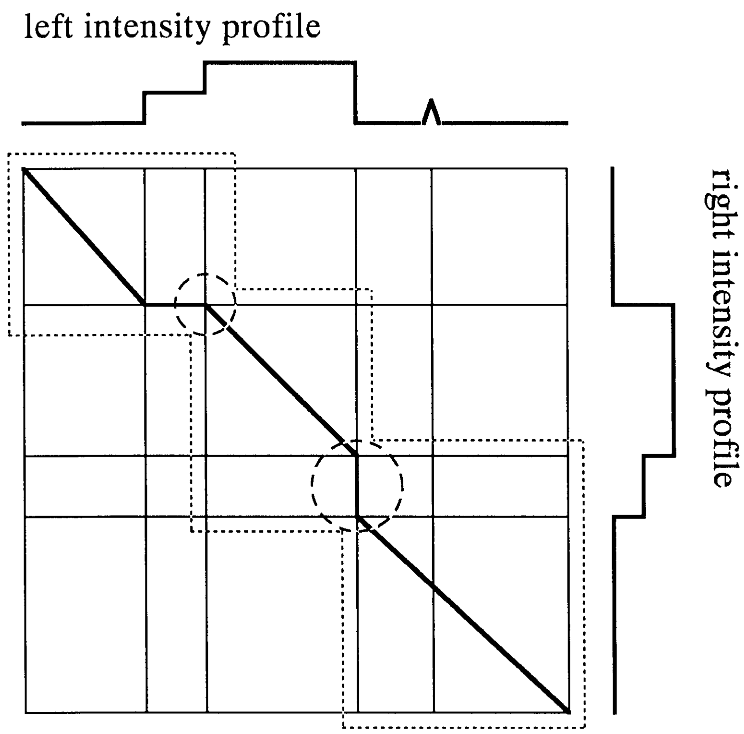


Fig. 3 A search plane for interval-based matching

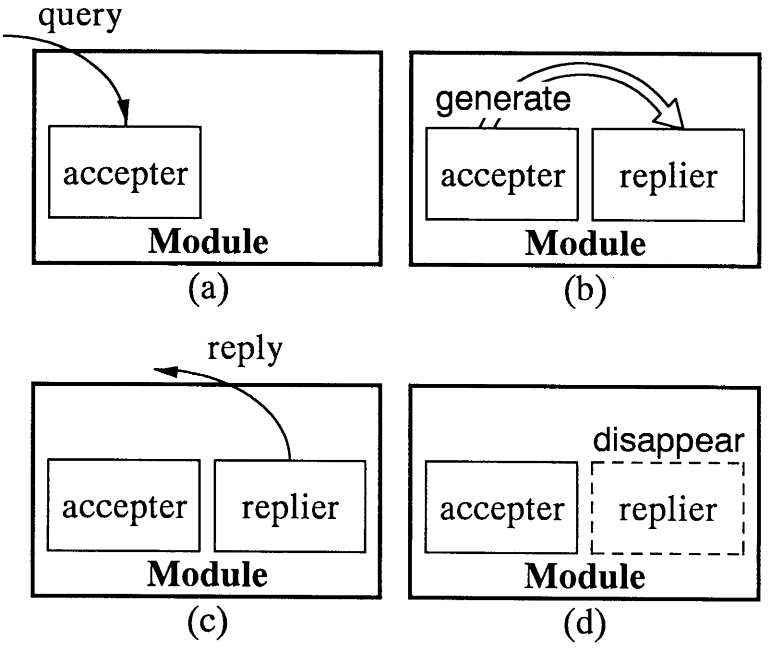
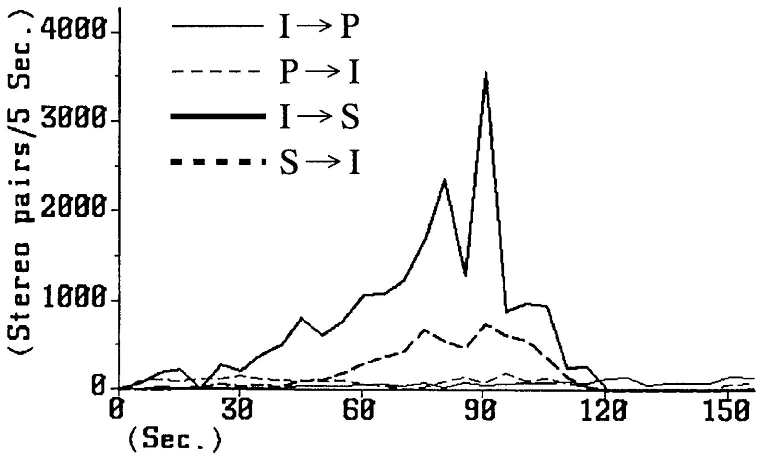
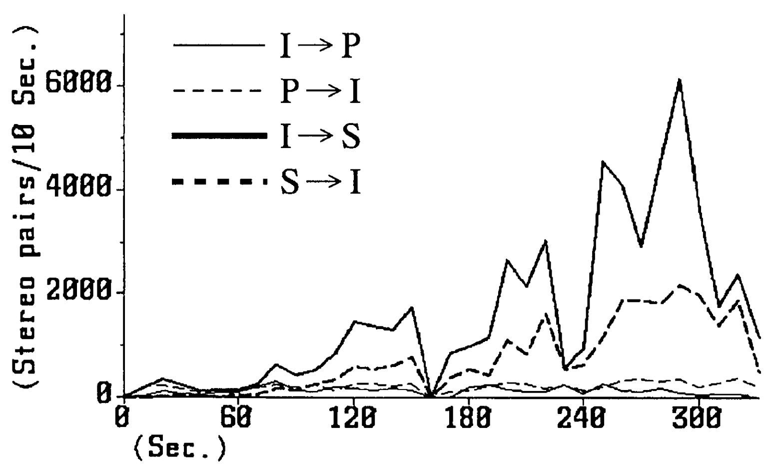


Fig. 4 Behavior of a module for inter-module communication



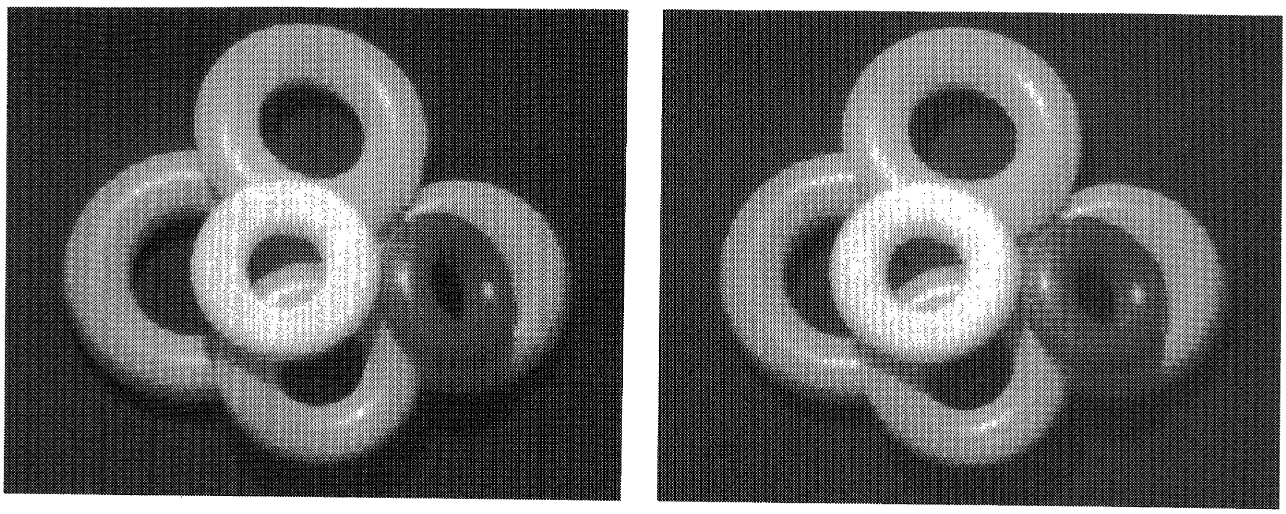
(a) Block scene



(b) Room scene

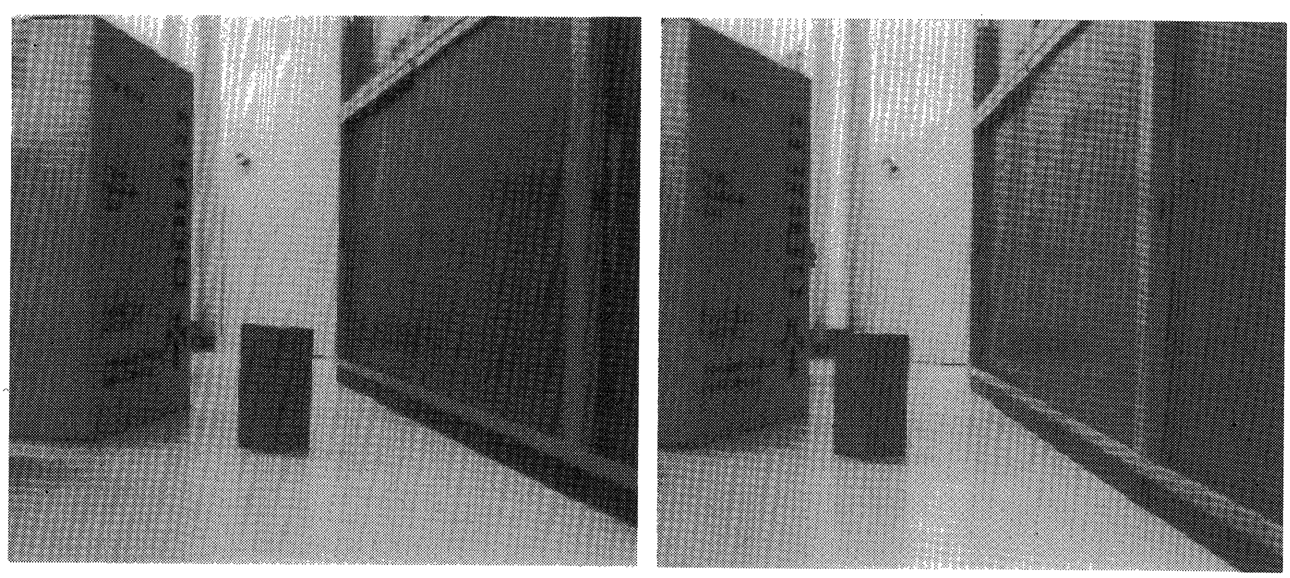
P : Point-based search module
I : Interval-based search module
S : Segment-based search module

Fig. 5 Transition of communication among stereo modules



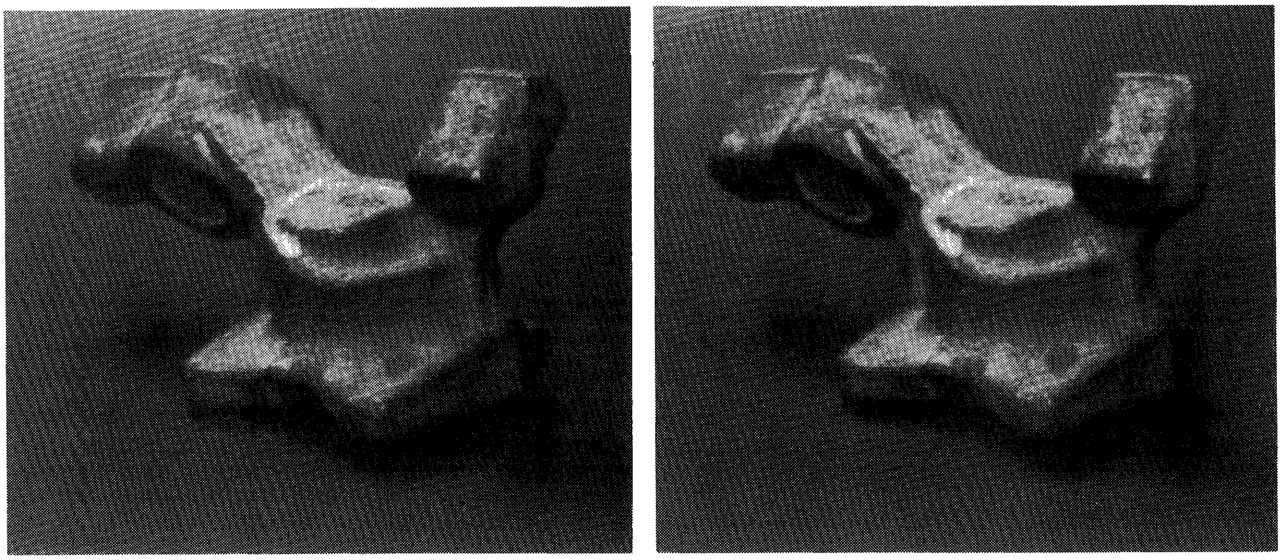
(a) Left image (b) Right image

Fig. 6 Block scene



(a) Left image (b) Right image

Fig. 7 Room scene

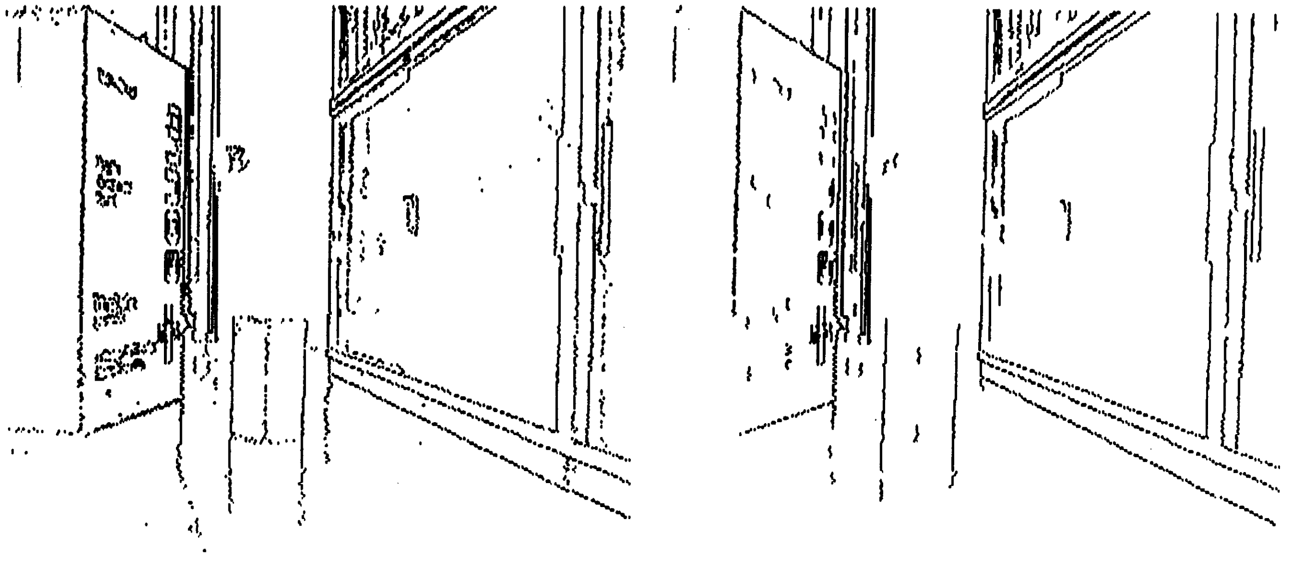


(a) Left image (b) Right image

Fig. 8 Component scene

(a) Edges (Left) (b) Extracted segments (Left)

Fig. 9 Edge images (block)

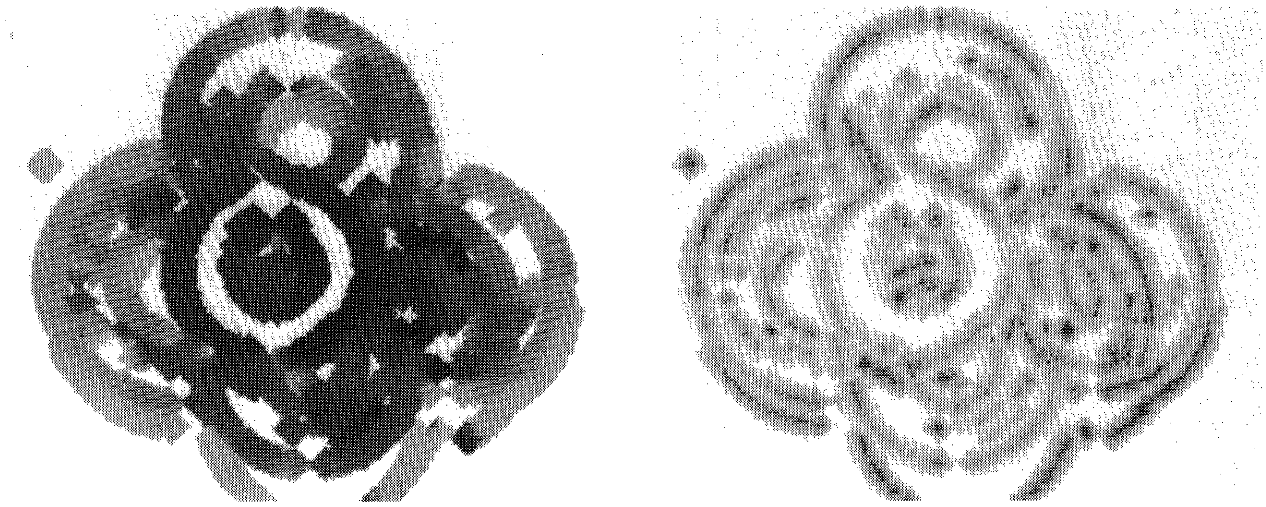


(a) Edges (Left)　　(b) Extracted segments (Left)

Fig. 10 Edge images (room)

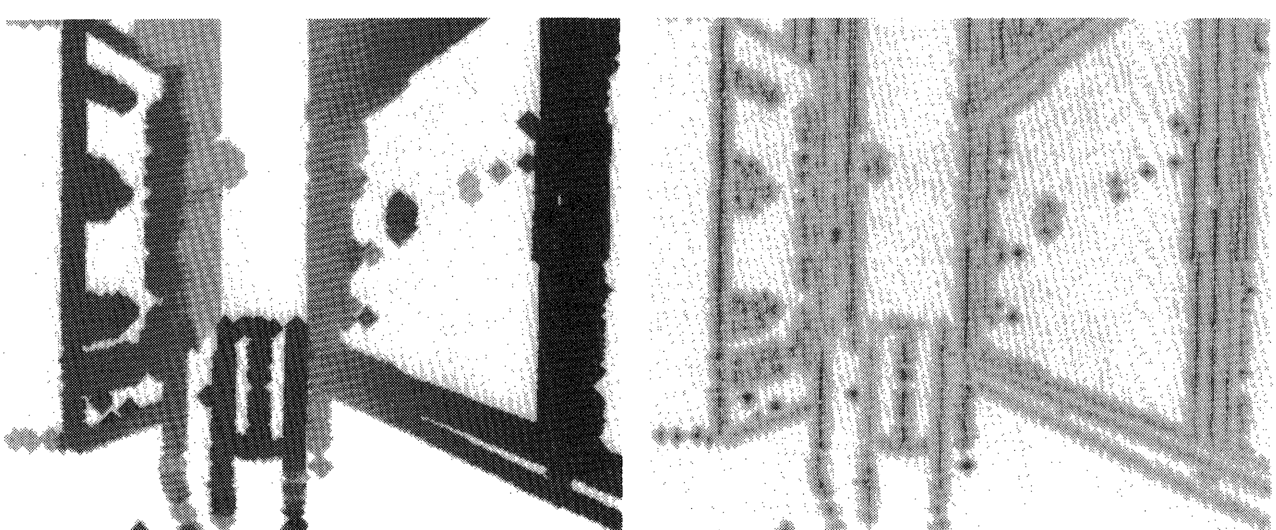
(a) Edges (Left)　　(b) Extracted segments (Left)

Fig. 11 Edge images (component)



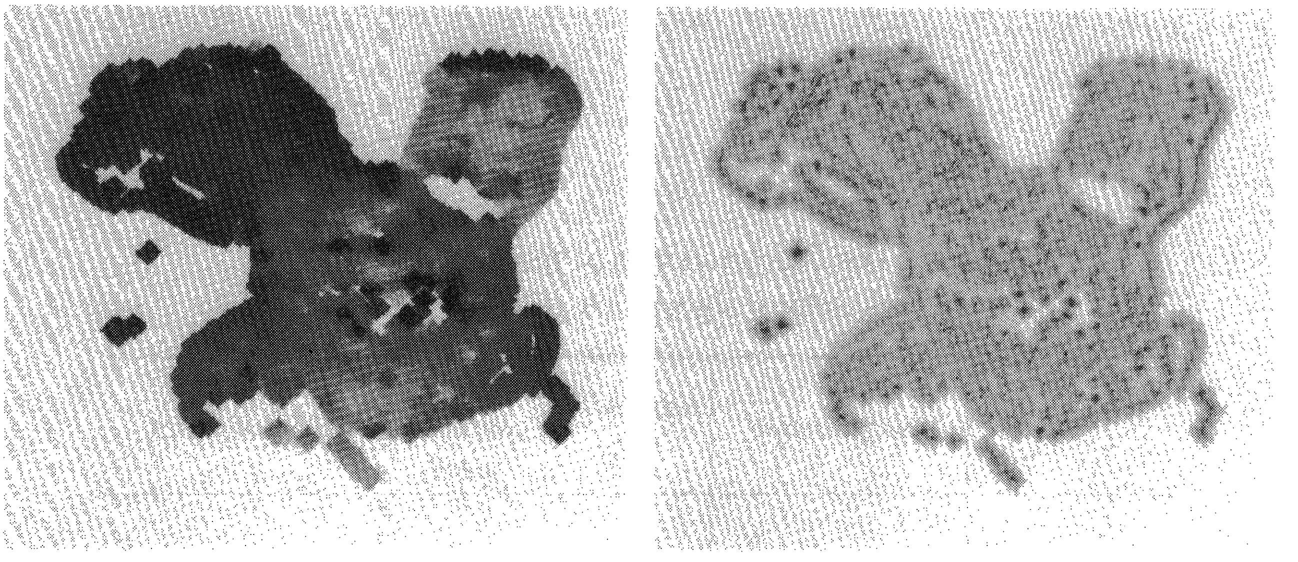
(a) Disparity map (b) Confidence map

Fig. 12 Final output (block)



(a) Disparity map (b) Confidence map

Fig. 13 Final output (room)



(a) Disparity map (b) Confidence map

Fig. 14 Final output (component)

Table 1 The characteristics of the three stereo matching algorithms

	image feature	application range	accuracy of correspon-dence	characteristics
point-based	interesting points	○	△	textural part
interval-based	intervals on the scanline	△	○	intra-scanline consistency
segment-based	connected edge elements	×	△	inter-scanline consistency

Table 2 Error rate in each matching algorithm

scene	with/without communication	point-based matching algorithm		interval-based matching algorithm		segment-based matching algorithm	
		false positive	false negative	false positive	false negative	false positive	false negative
block	without	4.3(%)	29.9(%)	4.0(%)	5.4(%)	8.4(%)	37.3(%)
	with	4.3	29.9	2.7	4.3	0.0	0.9
room	without	9.7	44.1	11.2	17.5	23.9	52.4
	with	9.5	44.2	7.8	14.6	0.9	10.6
component	without	8.8	33.3	10.4	14.1	15.5	41.1
	with	8.8	33.3	9.9	15.1	0.8	11.5

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AUTHOR(S)

Masaki WATANABE

Yuichi OHTA

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stereo vision, cooperative processing, algorithm integration, sensor fusion, parallel processing

ABSTRACT

In order to realize a flexible stereo vision system which can cope with a variety of scenes, we propose a new scheme to integrate multiple stereo algorithms in a cooperative framework. Each algorithm is implemented in a separate module and executed in parallel. The stereo correspondence obtained in each algorithm is stored in the module. Confidence of each stereo correspondence is evaluated based on the ambiguity in the search process and it is attached to the correspondence result. During the execution, each module communicates with other modules and offers subsets of its results to another by its request. The cooperation among the modules enables not only to improve the performance of each algorithm but also to make the integrated system highly adaptive to various scenes. A system integrating three stereo matching algorithms which use different kind of image features has been developed on a parallel computer to demonstrate the feasibility of our scheme.

SUPPLEMENTARY NOTES