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Pattern and Frontier-based, Efficient and Effective Exploration of Autonomous Mobile Robots in Unknown Environments

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Abstract

This paper proposes a method with which mobile robots can explore unknown environments efficiently and effectively. For mobile robots, developing exploration methods in unknown environments is a challenging target. Navigation for environment monitoring is necessary in order to explore efficiently in unknown environment. Although a frontier-based exploration can be seen as a conventional method, this method is not necessarily a global optimal planning method, because it explores for the local optimal in each situation; in the monitoring task, it could fall into the local solution, because it could not take into consideration the overall observation efficiency. The proposed method exploits the whole observation and knowledge about the area of the unknown environment. It is possible for the proposed method to establish a global plan in consideration of efficiency and effectiveness by integrating pattern and frontier-based exploration. In simulation, it is shown that the proposed method of pattern and frontier-based exploration is useful for exploring unknown environments efficiently and effectively.

Introduction

In recent years, environmental problems such as environmental destruction and reduction of wild animals have become serious and been gathering people's attention. We focused on researching environmental monitoring methods by autonomous mobile robots. Specifically, we use the robot called WAMOT (Waseda Animal Monitoring Robot) [3], which was developed by Waseda University as a mobile environmental monitoring robot. Figure 1 shows the monitoring flow by WAMOT. To enable the wide range monitoring, WAMOT needs a monitoring post, whose function is battery charging.

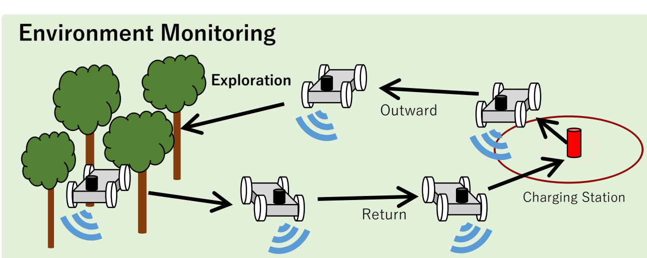


Fig.1 Monitoring post based strategy for environment monitoring

Conventional research on monitoring robots includes research by Ohashi et al. [1] and research by Xu et al. [2]. Ohashi et al. propose a method for utilizing multiple monitor robots equipped with multiple sensors in fields etc. If the multiple sensors detect a wild animal, the image of the animal can be uploaded to the cloud. The robot or drone judges whether the animal in the image is vermin, and the robot or drone takes an effective action for the vermin. The technology of communication in this system is established, but actual robot operation is not reported. The research by Xu et al. is drone monitoring, and they do not report terrestrial traveling robots.

As a conventional study of WAMOT, research by Tanaka et al. [3] can be seen, but Tanaka's autonomous driving control algorithm is affected by sunlight. In addition, it is difficult to estimate the self-position of WAMOT by GPS due to shielding by trees, their branches, leaves, etc. in the forest environment, which is the observation site. Therefore, a method for self-position estimation is needed. In addition, research on the navigation has not been done.

As described below, the task of this paper is to search efficiently in unknown environments so as to create an environment map, not to search full areas in the unknown environments. Therefore, considering the sensors' measurable ranges, route planning that maximizes the observation efficiency, which is the observation quantity (detailed below) per mileage, should be selected.

In unknown environment exploration, environmental information is not known beforehand. Therefore, it is impossible to estimate the environment beforehand and make an overall plan with good observation efficiency based on it. Our monitoring tasks do not know the environmental information in advance, but we assume that the area of the environment to be searched is known. Therefore, the robot always knows the area which is not observed and the area which has been observed.

B.Yamauchi compared exploration performance differences depending on multiple route patterns in the target search for observation map generation [4]. Among their route patterns, this paper utilizes the star type and the spiral type. Meanwhile, frontier-based exploration for the navigation in unknown environment exploration has been proposed by B. Yamauchi et al. [5]. In recent research, global / local frontier points are efficiently searched by Rapidly-exploring Randomized Trees (RRT). The point with the highest revenue in consideration of the estimated amount of observation according to the sensor range and the navigation cost from the detected search point is assigned as the next search point [6].

In case of the task of this paper, it is necessary to acquire terrain information and load inexpensive sensors for operation. Therefore, a depth sensor which is different from recent study [6] is mounted instead of 3D LiDAR. In this paper, we improve and apply frontier-based exploration to the sensors' ranges, observation target / range, etc. Frontier-based exploration maximizes local efficiency. However, there is no mechanism to optimize global efficiency. Therefore, we exploit pattern-based exploration for global efficiency, because we know the area of the environment to be explored. In addition, this paper proposes a method of supplementing missing parts by frontier-based exploration

Overview of WAMOT

WAMOT (Waseda Animal Monitoring Robot) was developed with the objective of creating an environmental monitoring map and an ecological map of animals. It is possible to monitor the environment where the undergrowth such as the forest grows[7], the sand on the coast, the ground snowy.

As shown in Fig. 2, WAMOT has independent motors on the left and right wheels. These wheels are synchronously controlled, and they turn by the difference of the left and right rotation. Each WAMOT body side can also be mounted in two or three wheels, allowing more robust environmental monitoring by changing wheels depending on the monitoring environment. As shown in Fig. 2, it is a motion model at the same phase and opposite phase respectively on the left and right sides.

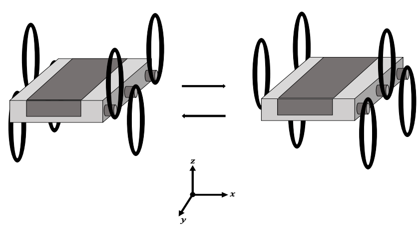


Fig.2 WAMOT model

System Configuration

Generally, autonomous mobile robots get autonomous ability by three processes: Localization, Mapping, Navigation. The flow of the entire system is shown in Fig3.

The sensor data acquired from various sensor systems installed in the robot is input to the Localization processing unit and Mapping processing unit.

The Localization processing unit mainly performs self-position estimation. In the Mapping processing unit, an environmental map is generated from the self-position estimation result obtained by Localization and the external sensor data, and finally a cost map is calculated.

Navigation processing is performed using the robot position information and environment map information calculated from these processing sections, and the robot is controlled.

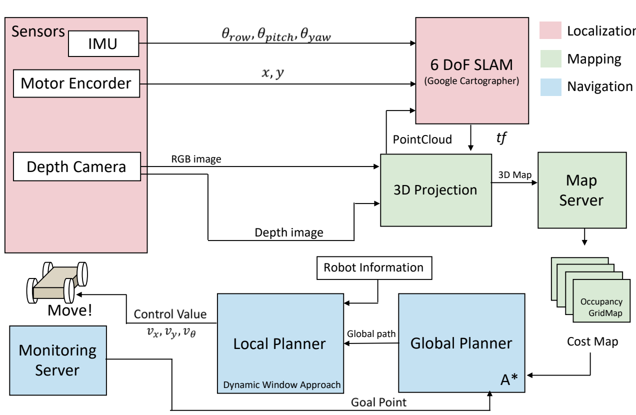


Fig.3 Whole system

WAMOT's Localization, Mapping, and Navigation are detailed in the following.

Localization

Sensors

As shown in Fig. 3, this system has Wheel Odometry, IMU and depth sensor as sensors, with Weld Odometry, IMU and depth sensor as input. A depth sensor is used as a method of acquiring a three-dimensional point group.

6DoF SLAM

LiDAR SLAM uses point clouds obtained from sensors, but there are also methods that combine odometry information and IMU information. Typical examples are Gmapping [7], HectorSLAM [8] and GoogleCartographer [9].

Mapping

In SLAM, we can obtain an environmental map of 3D point cloud. However, the computational cost of processing is large for large-scale 3D point clouds, and the point clouds obtained from sensors contain noise. Also, in outdoor environments, occlusion effects should also be considered. Therefore, a map (Octomap) [10] expressed in a three-dimensional grid is used. Octomap calculates voxels with high occupancy by using an octree (Octree) for a three-dimensional point group and outputs it as a map. In research on robots and drones, in many cases it is used as a three-dimensional map to avoid obstacles. The cost map is generated by using Octree, projecting the point cloud data into three-dimensional lattice and projecting it in two dimensions.

Navigation

Path planner

In this research, path planning and management of the whole monitoring are conducted in the following three ways. The first method is the Global Path Planner which performs route planning based on the cost information from the cost map. The second method is the Local Path Planner which considers the motion model of the robot based on the Global Path Planner. In this method, based on the latest observation result, plan the optimal route at that time and control the behavior. We use both of them as Navigation.

We also do Navigation by managing them with Monitoring Server which manages overall monitoring. The A * method [11], which is optimized in comparison with the Dijkstra method as the Global Path Planner, is used. The Dynamic Window Approach (DWA) [12] is used as the local path planner. In DWA, the control value is calculated directly from the speed group called Search Space considering the motion model of the robot. In Search Space, restriction on the speed considered from the perspective of obstacles Then, select the speed that maximizes the objective function.

Monitoring Server

Monitoring server manages overall monitoring. Generate a target point by performing global local route plan according to observation target and map. In this paper we propose a method on this topic in the following.

Proposed Methods

In the monitoring task of this paper, it is aimed to realize WAMOT's autonomous operation over a long period by autonomously performing electrical charging, where a charging station is placed at the center of the exploration target. The spiral type can be observed from around the charging station, gradually spreading the area in all directions, while in case of the star type, observation can be made in as step-wise manner in each direction. Therefore, both types have different advantages in monitoring.

Pattern based Exploration

First of all, WAMOT has the following differences in travel cost according to translational movements and rotational movements. Figure. 4 shows difference in power consumption in WAMOT's behaviors.

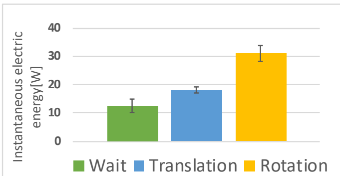


Fig.4 Instantaneous power consumption by actions

Rotational movements consume instantaneous power about twice as much as the translational movement. When considering the whole navigation plan, reducing wasteful energy consumption leads to an increase in observable areas and observation efficiency because it makes it possible to explore further using that saved energy resource. Therefore, we adopt the route pattern which selects many translational movements as shown in Fig.5.

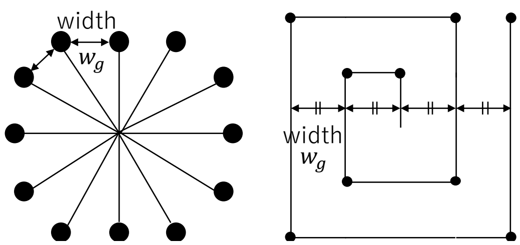


Fig.5 star type and spiral type

Relay points are placed according to these patterns, calculate the global plan is calculated by the global planner so as to loop around them in turn, and the path is followed by the local planner. The route pattern is generated according to the range of observation target which is known in advance and the goal width w_g depending on the sensor's measurable range. As shown in Fig.5, we create a module to generate two types of route patterns with goal width w_g as a parameter. Each optimum parameter is obtained experimentally.

Frontier-based Exploration

Frontier-based exploration is an exploration method for obtaining new information on an unknown environment proposed by B. Yamauchi et al [5]. Basically, Frontier Point which maximizes observation amount is set as the next search point.

We improve this Frontier-based exploration algorithm [7] to acquire search points that maximize the observation efficiency to solve this task.

Algorithm

Figure.6 shows the overall structure of the frontier detection in monitoring task

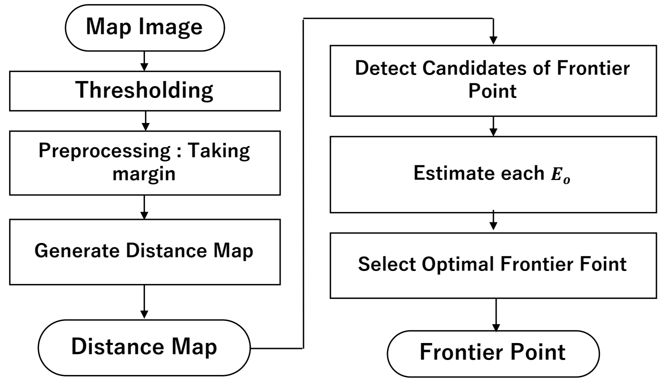


Fig.6 frontier detection in monitoring task

Generate distance map

As shown in Fig. 7, generating distance map based on observation map is a binary image: “observed” and “not observed”. Preprocessing is necessary for making the distance map calculable. The distance map is an image showing the distance from the “not observed” pixel to the nearest “observed” pixel by distance transform [14].

Fig.7 Generate distance image: left to right(map image, threshold image, preprocess image and distance map)

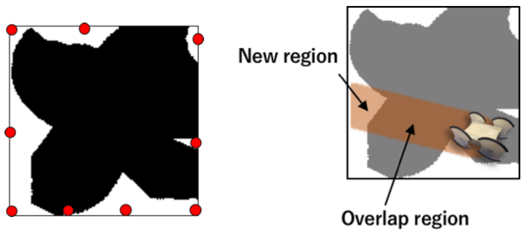
Detect candidates of frontier point

As shown in Fig. 8 (a), Selected pixels in descending order of distance from the distance map. Also, exclude it from candidates when it is within a certain distance to pixel which is already a candidate point at that time. The fact that the distance is large means that there are many unobserved areas in the vicinity; thereby, it may be computationally more efficient than doing the whole search.

Observation efficiency Estimation

As shown in Fig. 8 (b), All the global plans are computed between candidate points of frontier point and the robot position (approximated by a straight line). Based on these plans, a line of thickness of an arbitrary sensor range is drawn as an area that is actually the observation range when WAMOT passes through the route. The increased amount compared to the original observation map is each estimated increased observation amount ΔS_o. The observation efficiency E_o is estimated by dividing them by each path length L_t. Note that in the previous method, it is not considered the amount of observation while moving to the target point, but this method considers it.

$$E_o = \Delta S_o / L_t \quad (1)$$



(a) (b)

Fig.8 Candidates of frontier point. Detect candidates of frontier point (a) and observation efficiency estimation(b)

Select optimal Frontier Point

The estimated observation efficiency of each candidate points p of the frontier point is compared. Then, the pixel which takes the maximum is determined as the optimal frontier point $P_{optimal}$.

$$P_{optimal} = \underset{p}{\operatorname{argmax}}(E_o(p)) \tag{2}$$

Improvement of star type

In the star type exploration, exploration is performed by repeating the exploration to the relay point and returning to the charging station. Therefore, there are many overlapping regions of observation. In order to solve this problem, it is necessary to make exploration that does not overlap much considering the observation map. Specifically, as shown in Fig.9, when Observation Efficiency Estimation is performed and the estimated observation efficiency to the next target point falls below an arbitrary target observation efficiency, the target point is switched to the next point.

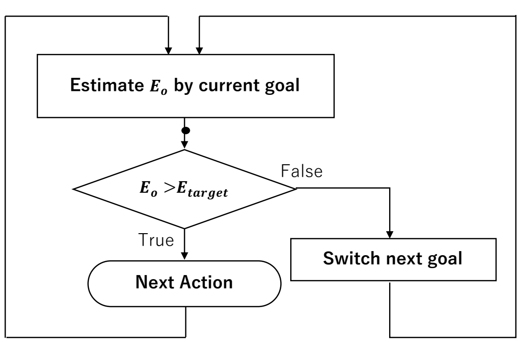


Fig.9 Algorithm of Observation Efficiency Estimation for star type.

Pattern and Frontier based exploration

As shown in Fig. 10, after performing pattern-based exploration with the star and spiral types respectively, the missing region is complemented using frontier detection. The frontier-based exploration is repeated until the observation rate R satisfies an arbitrary target observation rate R_{target} after clearing the target point generated by pattern-based exploration.

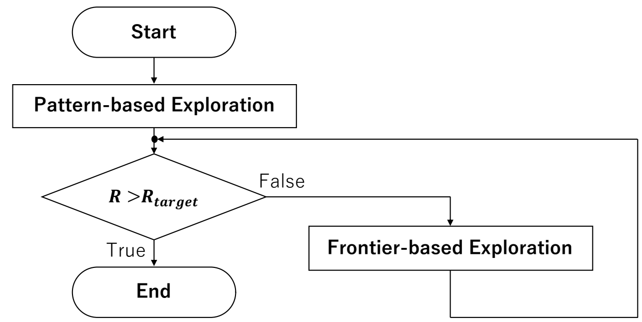


Fig.10 Pattern and Frontier based exploration Algorithm

Evaluation

We show the effectiveness of the proposed method that combines Pattern-based exploration and Frontier-based exploration.

In Experiment 1, the following methods are compared so as to ascertain the effectiveness of the proposed pattern and frontier-based exploration:

・***spiral type with frontier method*** : spiral type with frontier-based exploration.

・***star type with frontier method*** : star type with using the improved methods, which is proposed by this paper, and frontier-based exploration.

・***Only frontier-based exploration method***

In Experiment 2, it is shown that the monitoring is performed.

Experimental Environment

We use ROS [15] as the robot platform. We conducted experiments with Gazebo, which is a simulator environment (see Fig.11).

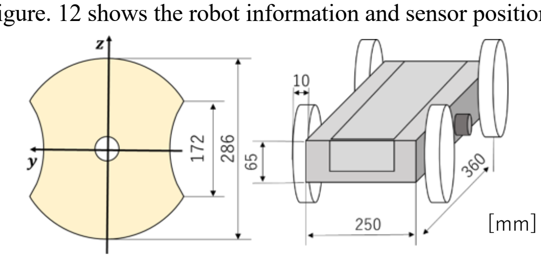
(a) (b)

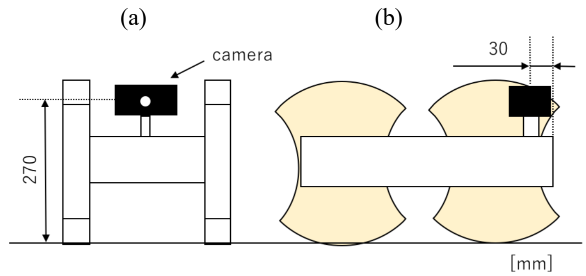
Fig.11 Experiment Environments

The planar environment (a) was used to compare the performance of the methods in Experiment 1. Forest environment (b) was used in Experiment 2.

Robot Configuration

Figure. 12 shows the robot information and sensor position.





(c)
Fig. 12 Robot Configuration
wheel type(a), body(b), sensor position(c)

Experiment 1

Experimented in advance, we chose high performance goal width with each method (described in parentheses of the method). We compare the four methods of the proposed method, star type and its improved type, spiral type and frontier-based exploration only. Also, star and improved star and spiral, as proposed, shift to frontier-based exploration after pattern-based exploration. Frontier-based exploration was set to end when the observation rate R exceeded 90 [%]. The observation range was 20x20[m^2]. The results are shown in Fig.13.

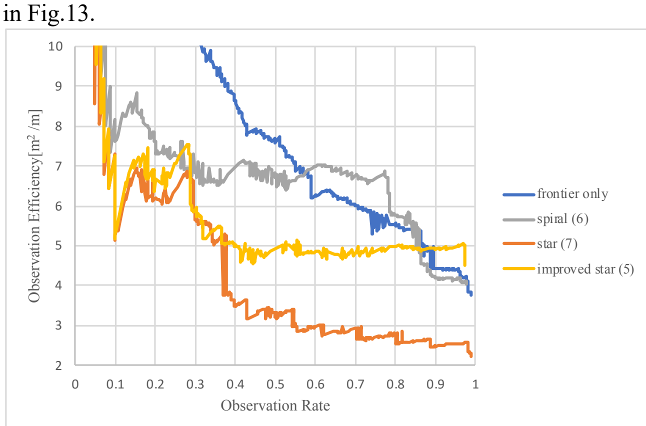


Fig.13 Environment 1 Results

Experiment 2

In order to verify whether the monitoring exploration can be realized in the simulator forest environment using the improved spiral and improved star type. The Frontier-based search was set to end when the observation rate R exceeded 90 [%]. The observation range was 20x20[m^2]. The results are shown in Fig.14 and Table.1. Discussions about the results are described below.

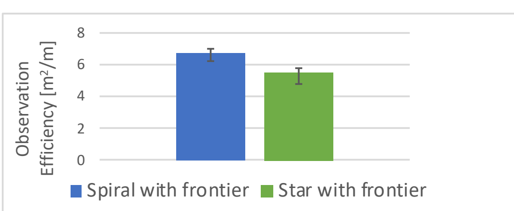


Fig.14 Environment 2 Results

Table. 1 Experiment 2 Results

type	w_g $[m]$	Ave.		
		E_o	L_t $[m]$	Time [sec]
Spiral with frontier	7.0	6.65	55.95	196.46
Star with frontier	6.0	5.48	72.12	309.97

Discussion

In Experiment 1, compared to star type, the improved star type achieved better performance, and it got close to that of the improved spiral type. In addition, the improved star type is ultimately more effective than only frontier method or the spiral type. The spiral type is also more efficient than other methods for 60-85[%].

This is because the optimal local policy cannot be established although it is optimal local plan for frontier-based exploration alone as originally assumed. Figure.15 is an example of only frontier method, but since it is selected as the frontier point with high observation efficiency from time to time, the turn around the target point is not optimized.

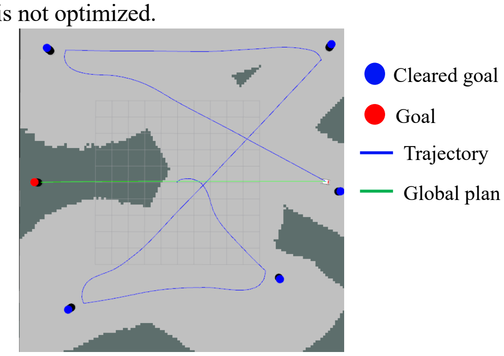


Fig.15 Example: only frontier method

On the other hand, the proposed method which is pattern-based and aimed at a certain degree of overall efficiency was able to exceed the performance. We think that it is possible to select these depending on the purpose of observing the charging station surroundings or gradually observing the observation range. Then it is more efficient to select spiral type or improved star type according to the target observation rate.

In Experiment 2, it was shown that it can be monitored by both type of improved star type and improved spiral type.

Conclusion

This paper has proposed a pattern for frontier-based exploration as an exploration method for a monitoring robot's observation in an unknown environment. We also have proposed a method to optimize both star type and spiral type and shown its effectiveness experimentally.

In these experiments, we show that pattern and frontier-based exploration are effective for monitoring strategy in unknown environment exploration.

In future work, in order to resolve the problem of local optimal in navigation, We would like to find an optimal solution for monitoring using deep level reinforcement learning which is an optimization method that maximizes long term value in order to perform global optimization.

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Jun Ohya earned B.S, M.S. and Ph.D. degrees in Precision Machinery Engineering from the University of Tokyo, Japan, in 1977, 1979 and 1988, respectively. He joined NTT Research Laboratories in 1979. NTT sent him to the University of Maryland, USA, for one year from 1988. He transferred to ATR, Kyoto, Japan, in 1992. In 2000, he joined Waseda University as a professor. In 2005, he was a Guest Professor at the University of Karlsruhe, Germany. Since 2014, he has been a professor at the Department of Modern Mechanical Engineering, Waseda University. His research areas include computer vision and machine learning. Dr. Ohya is a member of IEEE, IIEEJ, IEICE, IPSJ and VRSJ.

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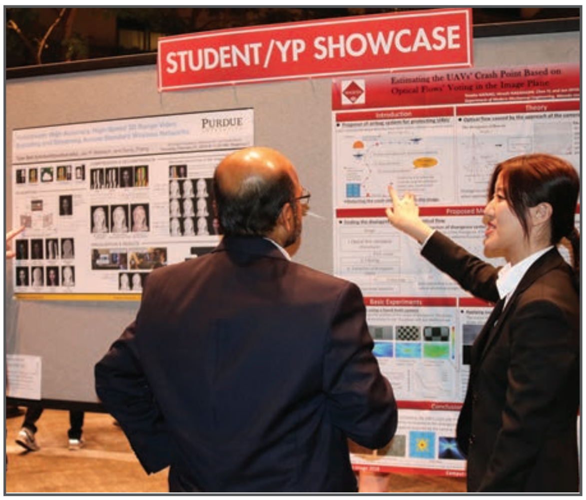

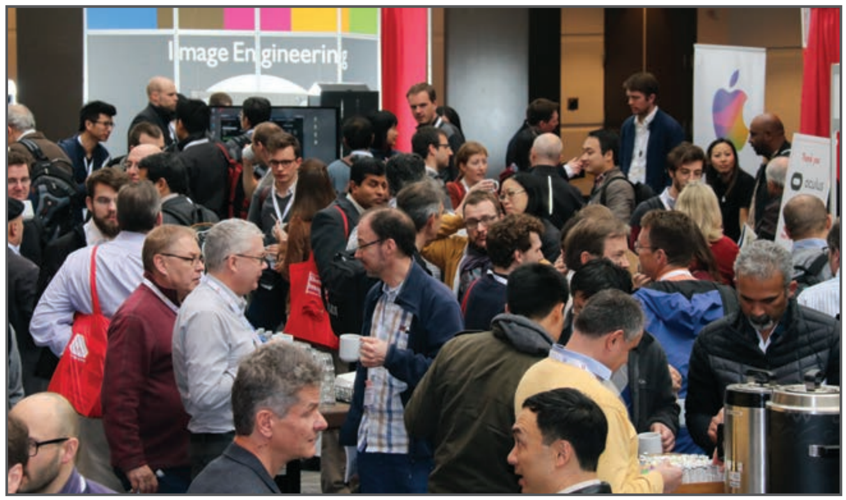

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