Autonomy of Firefighter Robots for Extinguishing Fire in Petrochemical Complexes

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論 文 内 容 の 要 旨

A national project of firefighter robots started at 2014 in Japan, and the main project target is petrochemical complexes fire disaster.　In Japan, petrochemical complexes fire disaster is usually caused by a major earthquake. Major earthquake happens about every ten years in Japan. Therefore, it is important to have a firefighter robot system prepared for the future petrochemical complexes fire disaster.

The motivation of this study is to enable the autonomy of firefighter robots at petrochemical complexes fire disaster. Firefighter robot is required replace firefighter men in a dangerous fire disaster. Because, petrochemical complexes fire disasters pose a high environmental risk because large fires and explosions can cause injuries, fatalities, and devastation. The use of firefighter robots can reduce the risk to firefighters. Such a system is comprised of several vehicles, such as a water-shooting robot, a hose-extending robot, and an exploration robot. An autonomous capability facilitates their control and enables many robots to be controlled by only a few operators.

This research target is the autonomy of water-hose-extension robot. The water-hose-extension robot extend the fire hose from the target fire location to the water pump. The purpose of water-hose-extension robots are to carry and extend water hose to a target location for supplying 4000 liters of water per second. Description of autonomy of water-hose-extension its difficulties are:

First, the autonomy of firefighter robot requires consistent map between aerial map and Simultaneous Localization and Mapping (SLAM) map in large area. The consistent map is required because firefighter man specifies the target position on the aerial map. While, the robots move by using SLAM map. The consistency between SLAM-map and aerial map is important for the robot to arrive at the target position. In addition, real-time consistent mapping is required in fire disaster because the petrochemical complexes fire disaster map changes in real-time by explosion and fire. (1) The difficulty of this part is real-time consistent mapping with aerial map in large petrochemical complexes.

Next, the water hose extension robot extends the fire hose from the target fire location to the water pump. Purpose of autonomy is for water hose-extension robot will extend the water hose from target location to the nearest water supply by putting the water hose on the road. (2) The difficulty of this part is path-planning for water hose extension requires minimum path radius 5 m to avoid bend on the water-hose path. In addition, during water hose extension, the path-planning need to react to obstacle in real-time in dynamic fire disaster environment.

Next, in fire disaster, the sensors used by autonomy can be damaged by the high heat. In such environment, the sensors are protected by heat cover by intervals; at first the robot open heat protector cover for sensors to collect data as the sensor temperature increases by fire heat, and next, the robot cover sensor from fire by heat protector to cool down the sensors temperature. (3) The difficulty of this part is to find a suitable parameter for heat cover interval to protect the sensor from damage and at the same time to have minimum error on the autonomy.

Finally, in extreme weather, the autonomy sensors such as LIDAR measure have many false data caused by the extreme weather. In this work, we focus on one part of extreme weather which is dense water-mist. (4) The difficulty of this part is to build robust sensing in dense water-mist environment for autonomy.

The main contribution of this study is the development of software module to solve the above-mentioned difficulties of the autonomy of water-hose-extension robot. Our approach and significant result are explained from chapter 2 to chapter 5:

In the second chapter, we proposed a solution fast SLAM 2.0 based on GPS and LIDAR to achieve real-time consistent mapping. The consistency of the SLAM map with aerial-map is important because human operators compare the map with aerial images and identify target positions on the map. The global positioning system (GPS) enables increased consistency. Therefore, this paper described two Rao-Blackwellized particle filters (RBPFs) based on GPS and light detection and ranging (LIDAR) as SLAM solutions for map consistency. We propose the use of Fast SLAM to combine GPS and LIDAR for the map consistency. The difference between the original Fast SLAM and the proposed method is the use of the log-likelihood function of GPS; the proposed combination method is implemented using probabilistic mathematics formulation. The map consistency was evaluated using sensor data measured in a real petrochemical complex in Japan ranging in size from 380-550 m. RTK-GPS data was used for GPS measurement, and its availability was 56%. Our results showed that Fast SLAM 2.0 based on GPS and LIDAR in a dense grid map had the best results for map consistency. There was a significant improvement of global consistency to aerial data, and the mean square root error was 0.65 m. To evaluate the local map consistency, accurate 3D point cloud data measured by Faro Focus 3D (accuracy ±3 mm) was used as the ground truth. Buildings sizes were compared; the minimum mean errors were 0.17

and 0.08 m for the oil refinery and management building area and the area of sparse building layout with large oil tanks, respectively. Consequently, a consistent map, which was also consistent with an aerial map (from Google maps), was built by Fast SLAM 1.0 and 2.0 based on GPS and LIDAR. We also showed that Fast SLAM 1.0 and 2.0 based on GPS and LIDAR could reproduce map consistency result with ten runs with a variance of ±0.3 m. These methods could also reproduce map consistency results with the best global accuracy of 0.52 m in the low RTK-Fix-GPS environment, which was 20.9% for a factory with similar building layout to petrochemical complexes. Therefore, significant result of this chapter is map consistency with an aerial map in a real-petrochemical complex. It is important for support of firefighter-men to send command to our water-hose-extension robot.

In the third chapter, we proposed a path-planning for water hose extension at large area with real-time re-planning for obstacle avoidance. To fulfill water-hose-extension layout constrains, we optimized a path-planner by; changing the planner motion model to prevent the backward motion for no bend on the path and the planner parameter to fulfill minimum path radius of 5 m to prevent bending. To fulfill real-time water-hose-extension in a large environment, we use two stage path-planning; stage one planner to reduce planning time and stage two planner is for a fast re-planning time. Here in, we developed two-stage Hybrid A* path planning. We use Hybrid A* for path-planning. We optimized Hybrid A* motion planning for no reverse motion by using Dubin motion model to fulfill water hose extension layout constraint. In a large environment, we use two stage path-planning using two resolution maps; For the first stage, we use a global path planner that makes a path using a low-resolution grid map of 2 m. The global path planner generates a path for an area of approx. 500 m × 1000 m in 10 seconds. In the second stage, we refine the path by using a local planner that uses a local map of 100 m × 100 m size around the robot with a high-resolution grid of 1 m. The local planner receives its sub-goal from the global planner and recalculates a local path in real-time. Therefore, the local planner can react to changes in the map due to obstacles in real-time. We evaluated the path-planning for water hose extension at large area with real-time re-planning for obstacle avoidance in simulated as well as real experimental data of petrochemical complexes. For a trajectory of 600 m, the result shows path fulfills the need of water hose extension layout which is; path have no backward motion, and the path radius is larger than 5 m. In addition, path re-planning time was in real-time for real data and simulated data. Therefore, the significant result of this chapter is that we could make a path for water hose extension layout at large area with real-time re-planning for obstacle avoidance.

In the fourth chapter, we developed a 3-D simulator with effects of fire disaster to evaluate suitable parameter of sensor heat cover interval in petrochemical complexes fire disaster. Main challenges are to evaluate the best sensor's heat cover interval parameter that can protecting sensor from damaged by fire and provide minimum error to autonomy. However, evaluation in actual fire disaster is not possible because we cannot generate large fires in actual petrochemical complexes. For this purpose, we develop a 3-D simulator of a petrochemical complexes with new fire disaster effects which are (1) effect of fire on LIDAR data and (2) effect of sensor's heat cover interval on LIDAR data. To simulate effect of fire on LIDAR, we experimented and analyzed real-effect of fire and the effect embedded in the LIDAR measurement simulator. To simulate of sensor's heat cover interval on LIDAR data, we calculate using heat transfer theory for the suitable interval ratio to protect the sensor from being damaged by fire which is 1 s measurement and 6 s sensor temperature cool-down. For the implementation on the firefighter robot, we add 3 s to cooling for movement of sensor's heat cover. As a result, we can build a 3-D simulator with fire disaster effect.

We evaluated suitable sensor's heat cover interval in the most difficult scenario in the petrochemical complex, has dimensions 1000 m × 600 m. Several interval parameters of sensor's heat cover based on the ratio 1 s measure :6 s cooling was also analyzed for minimum error on SLAM. SLAM is an important part for the autonomy. We used SLAM result as an indicator for autonomy result. The evaluation result shows the interval parameter is 1 measurement and 9 s sensors cooling which the best average accuracy of GPS and LIDAR based SLAM was in the range 0.25-0.36 m. Therefore, the significant result of this chapter, we fundamentally prove using heat transfer theory the interval ratio 1 s measure :6 s cooling is suitable to protect sensor from fire heat. For implementation on firefighter robots, sensor's heat cover interval 1 s measure and 9 s cooling have the minimum error for SLAM. The knowledge suitable sensor's heat cover interval parameter is important for application of water hose extension robot autonomy in petrochemical complexes fire disaster.

The fifth chapter presents robust LIDAR measurement in water-mist-filled environments. Disaster response robots cannot easily navigate through such environments because this data contain false data and distance errors caused by water-mist. We analyzed a method for recognizing and removing water-mist based on point cloud features and a distance correction method for reducing measurement errors. Laser intensity and geometrical features are used to identify false data. However, these features are not sufficient to measure a point cloud in water-mist-filled environments with 6 and 2 m visibility, as misjudgments occur. A laser beam penetration features were added to reduce the misjudgments. Support vector machine (SVM) and K-nearest neighbor (KNN) are used to classify point cloud data into 'water-mist' and 'objects'. We evaluated the method in heavy water-mist (6 and 2 m visibility). SVM has a better F-measure than KNN; it is higher than 90% in heavy water-mist (6 and 2 m visibility). The distance error correction method reduces distance errors in point cloud data by a maximum of 4.6%. A point cloud was successfully measured using LIDAR in a water-mist-filled environment. The method's recall (90.1%) and F-measure (79.4%) confirmed its robustness. Therefore, the significant result of this chapter is robust sensor measurement in dense water-mist environment for autonomy in extreme weather.

The sixth chapter presents the conclusion of this dissertation. In this dissertation, the main contribution is the development of software module to deal with difficulties the autonomy of water-hose-extension in petrochemical complexes fire disaster. At first, (1) we develop a fast SLAM based on GPS and LIDAR for a real-time consistent map with an aerial map in a petrochemical complex. It is important for support of non-expert user such as firefighter-men to send command to our water-hose-extension robot autonomy. Next, for the autonomy of water hose extension, (2) we developed path-planning for water hose extension layout at in a real-petrochemical complex with real-time re-planning for obstacle avoidance. Next, the autonomy of water-hose-extension have to move in fire disaster environment. The fire heat can damage the sensor. (3) we discovered suitable sensor's heat cover interval ratio 1 s measure: 6 s cooling to protect sensor from fire heat by the calculation of heat transfer theory and combination of 1 s measure and 9 s cooling which have best result for SLAM. The knowledge suitable sensor's heat cover interval parameter is important for application of water hose extension robot autonomy in petrochemical complexes fire disaster. Finally, the autonomy in real-application is required to operational including extreme weather condition such as dense water-mist. (4) for this purpose, we develop a robust sensor measurement in dense water-mist environment. The robust sensor detects and eliminate false data cause by water-mist. As a general conclusion, we develop software modules to dealt with the difficulties of the autonomy of water-hose-extension in petrochemical complexes fire disaster

論文審査結果の要旨

石油化学コンビナート大規模火災の放射熱量は 15kW/m^2 を超え，消防隊員の防護服が有する耐熱限界 2.6kW/m^2 を超えるため，消防ロボットによる消火が求められている。2014 年より総務省消防庁のプロジェクトが開始され，三菱重工業と東北大学がこの問題を解決するための放水砲ロボットとホース延長ロボットを開発している。1 ~2 名の消防隊員で複数のロボットを操縦できるようロボットの自律化が必要とされているが，大規模火災特有の種々の条件を満足しなければならない。

本論文は，その実現に必要なロボットの自律化ソフトウェアの設計と評価を明らかにすることを目的としている。すなわち，人間が動作指示に利用する航空写真と整合性の取れたロボット用地図をリアルタイムに構築する手法，ホース延長ロボットがホースを敷設するための制約を満たした経路をリアルタイムに計画する手法，を明らかにしている。また，これらの手法の火災現場における有効性を，石油タンク火災のシミュレーションにより評価している。さらには，濃煙環境で３次元計測を行うために，LIDAR の計測値から煙による計測ノイズを除去する方法を明らかにしている。本論文は，これらの研究成果を取りまとめたものであり，全編６章からなる。

第１章は緒論であり，本研究の背景，目的および構成を述べている。

第２章では，GPS と LIDAR のデータを融合することで，航空写真と整合性の取れたロボット用地図をリアルタイムに構築する方法を述べている。既存の方法と比較して提案手法が精度や歪みが少ないことを示すとともに，石油化学コンビナートに適用した結果，十分な精度が得られることを示している。

第３章では，ホース延長ロボットがホースを敷設するための制約を満たす経路を計画する方法を述べている。1 MPa の圧力で毎分 4000 L の水を流すため，回転半径が 5 m 以上でなければならないため，Hybrid A*アルゴリズムのロボット動作モデルと経路生成アルゴリズムを改良することにより，1000 m×600 m の環境でリアルタイムに，制約を満たす経路を生成している。実証事例として，石油化学コンビナートに開発手法を適用して，リアルタイムにホース敷設に適した経路を生成出来ること，障害物がある場合でも経路を再計画できることを示している。

第４章では，大規模火災を模擬するシミュレータを構築し，ロボット用地図を構築するソフトの火災時における適用可能性を評価している。火災の温度と波長の関係から，大型石油タンク燃焼時には LIDAR で対象が計測できないことを明らかにするとともに，高温火炎に対する LIDAR の計測モデルによって地図構築ソフトの火災時の性能を検証した結果として，大規模火災時でも消火活動に十分な精度で地図が構築できることを示している。

第５章は，濃煙環境において，LIDAR 計測値から煙に起因するノイズを除去して，煙の向こうの対象を計測する方法を述べている。視野 2〜6 m の濃煙環境では反射強度だけではノイズを除去できないことを示すと共に，LIDAR の反射強度とノイズ分布形状を特徴とした機械学習により，視野 2 m の環境でノイズ除去が可能なことを示している。また，煙による距離誤差を補正する方法を明らかにしている。

第６章は結論である。

以上要するに本論文は，消防ロボットの自律化ソフトウェアの設計と評価を明らかにしたもので，応用情報科学およびロボット工学の発展に寄与するところが少なくない。

よって，本論文は博士（情報科学）の学位論文として合格と認める。