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A survey on multi-sensor fusion based obstacle detection for intelligent ground vehicles in off-road environments

Key words: Multi-sensor fusion; Obstacle detection; Off-road environment; Intelligent vehicle; Unmanned ground vehicle

Corresponding author: Bo-yin ZHENG
E-mail: zhengboyin@mail.nwpu.edu.cn
ORCID: Jin-wen HU, https://orcid.org/0000-0003-2771-2393;
Bo-yin ZHENG, https://orcid.org/0000-0003-3908-9332

Motivation

- A single type of sensor finds it hard to satisfy the needs of obstacle detection because of the sensing limitations in the range, signal features, and working conditions of detection, and this motivates researchers and engineers to develop multi-sensor fusion and system integration methodology.
- This survey aims at summarizing the main considerations for the onboard multi-sensor configuration of intelligent ground vehicles in off-road environments and providing users with a guideline for selecting sensors based on their performance requirements and application environments.

Main idea

- To summarize the main considerations for the onboard multi-sensor configuration of intelligent ground vehicles in a complex environment.
- To provide users with a guideline to select sensors based on their performance requirements and application environments, such as weather, lighting conditions, and obstacle types.

1. Sensor characteristics and analysis

Table 2 Sensors for obstacle detection

Sensor	Type	Measurement	Resolution	Sensing range	Fog, rain, and snow robustness	Night time robustness	Cost
Sonar	Active	Range	Sparse	+	+++	+++	++
Lidar	Active	Angle, range, and size	Sparse	++	+	+++	+++
Radar	Active	Angle, range, size, and velocity	Highly sparse	+++	+++	+++	++
RGB-D (SL)	Active	Range, color, and direction	Dense	+	+	++	++
RGB-D (ToF)	Active	Range, color, and direction	Dense	+	+	++	++
RGB-D (stereo)	Passive	Range, color, and direction	Dense	+	++	+	+
Monocular camera	Passive	Color and direction	Dense	−	++	+	+
Thermal camera	Passive	Relative differences of radiation and direction	Dense	−	++	+++	++
Polarized camera	Passive	Polarization of reflected light and direction	Dense	−	++	+	+

Trade-offs need to be considered carefully among the following characteristics: active or passive; limited capability or all-weather day-or-night operation; range, direction, or color measurement; price.

We present a detailed analysis of the sensors by dividing them into three categories: range-based sensors, image-based sensors, and hybrid sensors.

Table 3 Category of sensors used for intelligent vehicles

Sensor	Vehicle
Range-based	Lidar; radar; sonar
Image-based	RGB monocular; infrared thermal camera; polarization camera
Hybrid (RGB-D)	RGB stereo; structured light; time-of-fight (ToF)

2. Multisensory fusion methods and comparisons

Table 6 Fusion method applications and analysis

Type	Method	Reference	Fusion level	Main contributions (+) and limitations (−)
Probability-based	Grid map	Sock et al., 2016	Decision	+ Easy implementation for traversable map generation + Ability for non-linear systems − Computationally intractable in high dimensions
	Kalman filter	Cho et al., 2014; Asvadi et al., 2016	Decision	+ Widely adopted and easily implemented for moving object tracking + Offering an analytical solution to the dynamic system − Limited in handling non-linearities
	Particle filter	Liu and Sun, 2012	Decision	+ Widely adopted and easily implemented for moving object tracking + Being able to deal with non-linearities − More computation burdens than those of KF-based methods
Classification-based	SVM	Li QQ et al., 2014	Feature	+ Widely used for road detection + Being able to deal with non-linearities − Hand-selected features − High complexity in large-scale tasks
	CRF/MRF	Häselich et al., 2011; Xiao et al., 2018	Decision/ Feature	+ Widely used for image labeling and point cloud labeling + Applications for road detection and terrain classification − Complex and time-consuming for energy minimization functions
	Deep learning	Chen XZ et al., 2017; Ku et al., 2018	Feature	+ Widely used for 3D object detection in urban scenes + No hand-selected features before the classification step + An end-to-end detection process − High storage and computation requirements
Inference-based	Fuzzy logic	Zhao et al., 2014; Wei et al., 2018	Decision	+ Adopted mainly for classification confidence fusion + Intuitive approach to deal with vague data − Choice of good membership functions and fuzzy rules strongly influencing fusion reliability
	Evidence theory	Chavez-Garcia, 2014; Starr and Lattimer, 2017	Decision	+ Adopted mainly for classification confidence fusion + Being enable to fuse uncertain and ambiguous data − Inability for fusion of highly conflicting data and incapacity to deal with data imprecision

There are mainly two purposes of fusion-based methods: redundancy and complementarity. We review and compare the existing sensor fusion methods in three categories: probability-based, classification-based, and inference-based.

3. Prototype systems and applications for obstacle detection in diverse environments

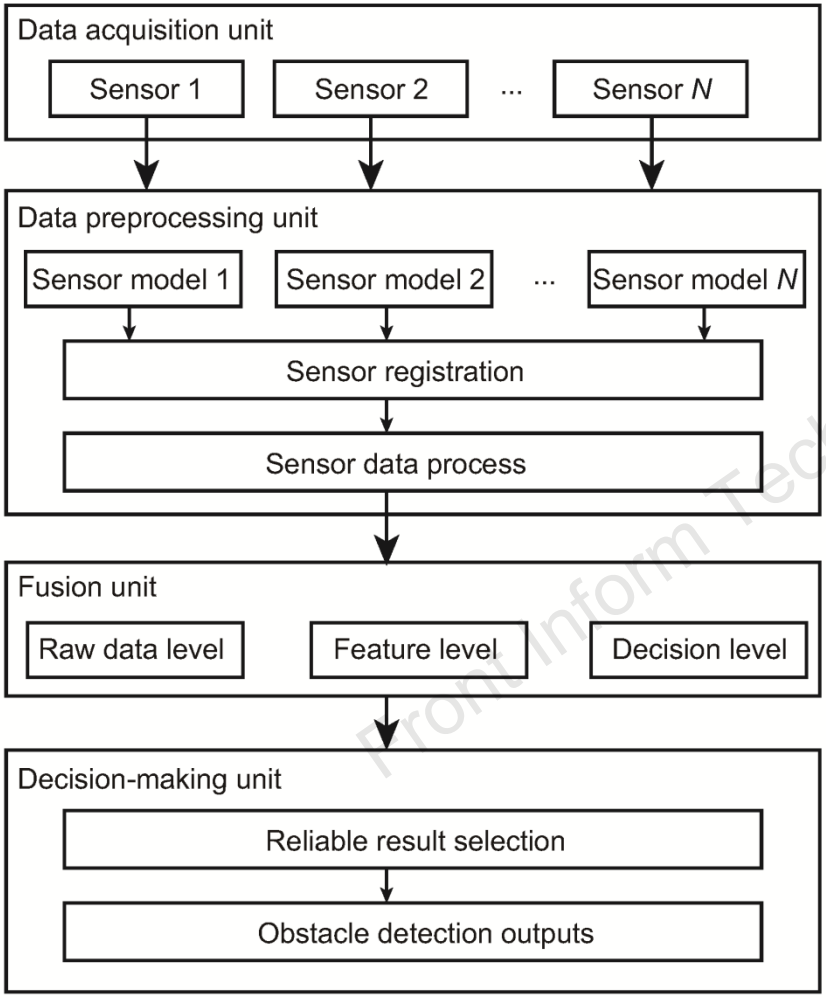

Fig. 1 Architecture of a multi-sensor fusion obstacle detection system

Applications with different types of obstacles:

- On-road obstacle detection
- Convex obstacle detection
- Concave obstacle detection
- Water hazard detection

Applications for adverse environments:

- Low visibility detection
- Adverse weather detection

4. Emerging technologies and challenges

Intelligent control of unmanned vehicles is greatly constrained by sensing and communication technologies. More and more efforts have been devoted to the emerging technologies, such as **Internet of Things (IoT)**, **vehicle networks**, **low-cost high precision sensors**, and **cooperative detection systems**, to enhance the capability of environment perception. Most of them are still under development with a lot of technological barriers and challenges to overcome.

The main emerging and challenging technologies include:

- **Internet of Things (IoT)**
- **Reliable wireless communication**
- **Sensor technologies**
- **Asynchronous information fusion**
- **Heterogeneous platform cooperation**

Conclusions

- We have reviewed obstacle detection methods and applications based on multi-sensor fusion for intelligent ground vehicles in off-road environments.
- Advantages and disadvantages of commonly used detection sensors, multi-sensor configurations, fusion methods, obstacles, and suitable environments have been analyzed and compared.
- The architecture of the multi-sensor fusion obstacle detection system has been presented, followed by a review of the existing prototype systems and their applications.
- The integration of emerging technologies for obstacle detection tasks has been discussed and future challenges for obstacle detection have been suggested.

Jin-wen HU received the BS and MS degrees from Northwestern Polytechnical University (NPU), Xi'an, China, in 2005 and 2008, respectively, and the PhD degree from Nanyang Technological University, Singapore.

He is currently an associate professor at the School of Automation, NPU. His current research interests include multiagent system, distributed control, unmanned vehicles, and information fusion.

Chun-hui ZHAO received the BS degree from the School of Mechanics, Southwestern Jiaotong University, Chengdu, China, in 1996, and the MS and PhD degrees from the School of Automation, Northwestern Polytechnical University (NPU), Xi'an, China, in 2003 and 2008, respectively.

He is currently an associate professor at the School of Automation, NPU. His current research interests include vision-based navigation, image processing, and target tracking.

Zhao XU received the BS and MS degrees in automatic control from Northwestern Polytechnical University (NPU), Xi'an, China, in 2005 and 2008, respectively, and the PhD degree in control and instrumentation from Nanyang Technological University, Singapore, in 2013.

She was a Research Scientist at the Institute of High Performance Computing from 2012 to 2014. Since 2015, she has been an assistant professor at the School of Electronics and Information, NPU. Her research interests include control, data-based diagnosis, and prognosis.