MARC - Modular Autonomous Adaptable Robot Concept

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Abstract— **The paper introduces a novel modular and adaptable payload concept for plugging in sensor and actuator platforms such as 3D LIDAR and visual sensor systems and robot manipulator and gripper systems. Integration, programming and operation of heterogeneous robot systems (such as mobile manipulators or robots in a machine network) are very complex tasks for plant operators. Heterogeneous system components have to be orchestrated (via proprietary interfaces) by higher-level control systems. Robot programs are created offline, in proprietary tools, and used through macros. System components are generally not compatible and interchangeable across manufacturers. These have to be programmed separately in manufacturer-specific tools. Cross-component debugging is difficult. The operation of complex systems is difficult, requires intensive training, and is currently limited to simple graphical user interfaces (GUI). As part of process optimization, it is usually necessary to optimize process points during the start-up phase. This requires highly skilled personnel capable of robot programming at the plant operators site. The combination of heterogeneous robot modules results in many new hazardous situations. It is therefore necessary to include an appropriate safety concept. The goal is to design a robot payload concept with a plug-and-play approach to be used as a modular and flexible unit. This shall reduce the effort for system integration and sensor calibrating significantly and provide a customized perception of the environment during certain work processes. The modular, autonomous and adaptable robot concept with several sensors and hardware components was implemented as a prototype on a rescue robot. The modules have already been integrated on other autonomous vehicles for exploration and dexterity tasks.**

I. INTRODUCTION

The automation of vehicles and different robot platforms has already been successfully implemented in a large number of use cases and applications . This includes the auxiliary and piloting functionalities of modern cars, unmanned shuttles and special purpose vehicles for tasks like transportation, construction, farming, search and rescue or surveillance. Especially within the automotive sector the ongoing development of systems for highly automated driving has made significant progress. The architecture of such a system is typically optimized for specific tasks like real-time sensor data processing, reliable on-board communication and vehicle control. Fundamental elements include (i) control data communication architecture, (ii) central domain controller, (iii) actuation systems, and (vi) environmental awareness and localization systems. All these components are typically highly specialized and adjusted to the domain of road traffic. Hence, the transition towards other domains like unstructured environments or flexible work processes is challenging and requires a significant research effort. When transferring technologies onto a platform like the one presented, there are several obstacles that must be overcome. The high levels of flexibility towards different application areas as well as the significantly different cost level are main factors that must be considered. Autonomous operation of mobile platforms imposes challenges not only in terms of technological hurdles, but also in form of a steadily increasing level of system complexity. Autonomous systems are increasingly more often used in cluttered and unstructured environments. Compared to arranged working cells, flexible sensor systems are needed to pick up the varying, dynamic environment. Thus, visual information is necessary to complement classical sensors like laser scanners or radar. The latter class returns a quantified result which can be used directly for feedback control. The modern, visual systems produce a vast amount of data, which cannot be used for control directly. The processing of this data to a lower dimensional to extract obstacles, distances and velocities is a necessity to be used on an industrial system in real-time. Cross-system communication and coordination of machines from different manufacturers is complicated by proprietary APIs. It is virtually impossible to exchange modules with devices from alternative manufacturers. This makes it difficult to integrate devices that meet the requirements (range, payload, speed, ...). Often data (e.g. measurement results of external sensors) must be integrated into the robot program code or robot systems must be connected to higher-level control systems via application- or user-specific interfaces. User standards for these interfaces are a first step for a manufacturer-independent standardized interfaces and are a prerequisite for universal interchangeability in the sense of Plug and Produce.

Complex, heterogeneous, modular robot systems require manufacturer- and user-independent standardized interfaces based on open communication standards and information models in order to enable interoperability and integration. Figure 1 shows a self developed rescue robot with a modular and flexible playload concept. This paper endeavor addresses a research need to open up possibilities in previously unfeasible, complex automated operation and manipulation scenarios of great practical impact. Some of the main problems that motivate the research aspects are based on the fact, that reliable localization within a diverse and changing environment is still problematic. Existing technologies often perform

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well under certain conditions but might become useless or disadvantageous in other situations like e.g. indoors. During automated operations, it is also essential to achieve certain accuracy in perception and mapping to perform certain tasks. The complexity of work processes in a dynamic environment and manipulation by the system itself makes tasks like sensor fusion and mapping especially challenging.

Fig. 1. Rescue robot with payload concept

II. STATE OF THE ART

A. Heterogeneous robot systems and mobile manipulators

Heterogeneous robot systems are robot systems that either combine several robots of the same or different design (linear, articulated arm, mobile robots) or robots with complex machines (e.g. injection moulding machines). Typically, external sensors, measuring systems, a connection to higher-level control equipment and safety systems are required to implement the desired function. A mobile manipulator is a system consisting of a self-propelled base and a robot arm. With the increasing number of system components and action options, disproportionately higher demands are placed on the control of the overall system. Therefore, even though promising prototypes have been developed [7], [17], [13] in terms of research, only a few highly integrated prototypical solutions are available [4], [1], [23]. Since the modules in the systems mentioned are not interchangeable, many mobile robot systems and automated systems are not flexible enough to be used for rapidly changing tasks. This is one of the biggest obstacles to widespread use, including in small and medium-sized enterprises [8]. An overview of the current state of the art as well as modern areas of application for Automated Guided Vehicles (AGV) can be found in [15]. Manufacturers often integrate mobile robots, navigation and safety equipment and peripherals into proprietary overall solutions. Data interfaces for material flow systems are proposed as a uniform communication standard between the system components of an AGV [20]. The aim of this project is to make hardware- and manufacturer-independent, integrable, interchangeable and thus more flexible in application, in order to be able to engineer more easily heterogeneous robot systems.

B. Robots for fire fighting and extinguishing operations

Over the past decades, a number of robots and technologies for fire fighting and extinguishing operations have been developed to support customers and disaster preparedness measures. Some of them are visionary and innovative like autonomous robots that integrate into the responder team, see Figure 2. Others focus more on the concrete solution of a practical problem such as new sensor systems such as ground penetrating radar. UGV (Unmanned Ground Vehicle) is an increasingly popular application in various industries. UGVs are used more and more not only in the military, security research, agriculture and logistics, but also in the handling of hazardous waste and radioactive waste.

Fig. 2. TAUROB, Colossus, EmiControl und THERMITE RS1-T3

C. Hybrid mobile robots with plug and play sensor modules

The modular robotic system is the next generation in robotics, production and logistic [2] [14] [9], cyber-physical systems [10] and unmanned systems. This innovative and affordable family of robots is based on a number of principal modules, giving a range of different application-specific baseline variants. These baseline variants can support other specialist modules according to individual user requirements. In comparison to previous systems, the modular system provides greater mobility, payload capacity and duration with reduced operator workload, reduced training requirements, and reduced life cycle costs. The development of mobile automation solutions opens up new markets and thanks to advanced standardization, it also presents a challenge for the implementation of highly flexible production [3] [9]. The technology transfer of research facilities has made an essential contribution to robotic research and advance development with the development of the Open Source Robot Operating System [12]. Several other robotics software platforms have already been implemented for example CLARAty [11], Miro [16] or Player [5]. Many software components such as autonomous navigation, path planning, 2D/3D image processing can be used for application development. In addition industrial networks (HTTP-RPC technology, OPC UA, etc.), web technologies for status information have already been implemented.

D. Interoperability and Integration

Interoperability is a necessity in distributed and heterogeneous systems to realize complex systems and flexible processes [20]. Enterprise Integration and Interoperability explores the dimensions of integration of modular systems that solve a larger task together. Modularity allows the system to adapt to changes and exchange data via interfaces. Various approaches exist that support a complex, adaptive system [19]. Three elements support the engineering of an integrated and modular system: (a) A uniform interface (API) for querying data and transmitting commands. (b) A data exchange format and information model including the corresponding semantic description of the data and commands. (c) the possibility to orchestrate the systems (e.g. via processes). These three elements are particularly challenging when both humans and robots act interoperable as collaborative systems [21] [22] [18].

E. Programming and robot middleware

[6] gives an overview of the development of middleware systems. Due to its complexity and interaction with autonomous systems, robot middleware is therefore of great importance for the heterogeneity of sensor/actuator hardware and applications, the improvement and simplification of software design and quality, and the concealment of communication complexity. Orocos as Open Robot Control Software includes utility functions from the fields of kinematics, real-time communication and has control and identification as application focus. ROS [12] is an open source, meta-operating system for robots and currently the most widely used middleware which provides services from hardware abstraction, device drivers, utility functions, inter-process communication and package management and provides tools for visualization and simulation. ROS-Industrial is an open source project that tries to transfer the capabilities of ROS to industrial manufacturing automation. The ROS-Industrial repository contains interfaces for common industrial manipulators, grippers, sensors and field bus systems. The project also offers software libraries for automatic 2D/3D sensor calibration, motion planning or developer tools, such as a Qt ROS plug-in and training documents and workshop materials. ROS enjoys great popularity in academic circles, but despite intensive efforts in specially founded consortia ROS industrial is little used industrially.

III. PAYLOAD CONCEPT

Heterogeneous robot systems, such as mobile manipulators or injection moulding machines with integrated robot systems, are complex in design, programming and operation, since different components must be integrated and function reliably by the plant operator. The main goal of this project is the implementation of a modular robot system, which is dedicated to be used by robotics professionals during the development and programming and by untrained personnel for easy implementation and intuitive operation of complex and heterogeneous robot systems. The approach includes the development of standardized interfaces, the development of a configuration and programming framework, innovative operating features for untrained personnel, and the development of a new robot system. The development of safety concepts and safety sensors that enable the safe and productive operation of such robot systems. Special attention is paid to the cooperation between man and robot system. In order to demonstrate the universal applicability, the project results will be demonstrated in several very different application-oriented scenarios.

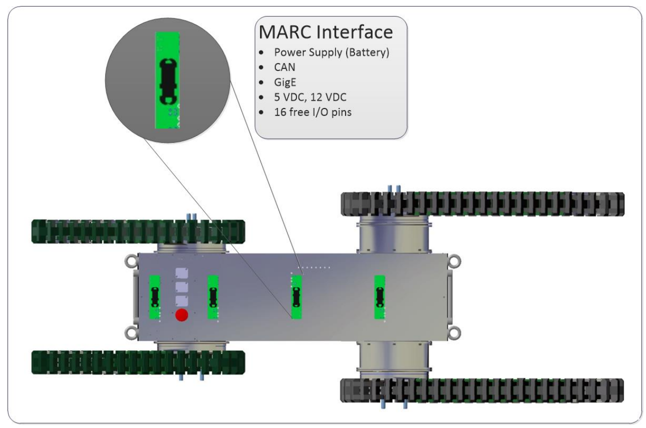

Fig. 3. Multiple Robot Platform (COBRA) with four MARC interfaces

A. Concept and Multiple Robot Platform (AMoWA - Vehicles)

MARC's flexible functionality allows third parties to design their own modules and gives the robot user the ability to integrate components that are automatically recognized via a self-defined interface, which module is located at which module location. The operator can also use a configuration file to define parameters of the robot with the already developed modules. For the end user, the automatic recognition and configuration of devices and attachments is a significant advantage for the simple and efficient operation of complex robot systems. When the robot modules are attached to the carrier vehicle, they are automatically detected by the middleware layer, which loads the appropriate software and updates the robot model. The modular connector is suitable for transmitting signals, power, high current, high voltage and coax in a single interface (CAN, RJ45 (GigE), Power supply (Battery), 5V, 12V, free I/Os). Figure 3 shows a prototype with four interface to carry four different modules. A Samtec connector is used for the payload concept, which is also suitable for transmitting power, signals, data or media. The modules are assembled and disassembled without tools, which allows the user to configure the robot quickly depending on the application.

Fig. 4. MARC for Autonomous Mobile Work Assistance (AMoWA)

B. Optimized First Responder Operation and Domain Modeling

For optimal mission planning, the modular robot concept allows the robot carrier platform to be ideally equipped for the upcoming application or operation, see Figure 4. A uniform interface ensures communication between all robot components on the market, covering all common field-bus systems and Ethernet-based systems. The payload concept have a Plug and Play module system, which reduces the use of special robots and machines as a modular and flexible robot or vehicle in the future and will strongly support the associated flexible application. By supporting the emergency forces with a flexible robot system, the mobile robot can be equipped with the necessary modules specifically for the area of application. The robot itself continuously sends data, which is recorded and analyzed to describe and record the situation and the environment. These data are of great value for the analysis of a mission. When evaluating the data after the operation, it can be concluded whether the robot system has worked efficiently or whether there is potential for improvement. Especially in the detection of POIs "False Positive" detections can occur again and again. When evaluating the sensor data, the algorithms can be refined and the false detection rate can be reduced for further applications. But not only the robot systems can be improved by the evaluation of the data, also the general use of different modules can be reconstructed and analyzed on basis of objective data. In addition, real data from a real scenario is obtained for the training of the emergency forces and can be used to explain to the trainees possible sources of error or smooth processes in real situations. Thus, the training can be optimized and the task forces to be trained are better prepared for the real scenarios. During operations with unknown hazardous substances, the emergency forces are exposed to great dangers. The persons concerned are exposed to high risks, as there is often only little reliable information available about the overall situation when planning operations. In order to be able to carry out targeted planning, information about the local situation and the intensity of the source of danger is required. For underground operations, there are usually digital plans or paper plans of the locations to be investigated, but these can be outdated or no longer correct due to the disaster to be investigated. For example, fire or explosions could have caused parts of the infrastructure to collapse. Furthermore, not only the local situation is important for the emergency forces, but also the spread of hazardous substances contained therein.

C. Developed MARC Modules (AMoWA - Components)

The improvement towards a versatile, mobile system which integrates state-of-the-art technologies in autonomous driving and novel approaches for situationally-aware operation clearly exceeds the capabilities of existing solutions on the market of unmanned ground vehicles.

- Exploration sensor system (LIDAR, RGBD sensors, GPS, Radar, Stereo vision cameras)
- Gas sensor module (Automess and Drger XAM7000)
- Computational module: Intel-PC, NVIDIA Xavier, NVIDIA Jetson TX2, ...
- Manipulator and gripper systems

D. Visualization and Usage of Robot and Sensor Modules

However, the available operator interfaces require expert knowledge and must be operated by specially trained personnel. More intuitive user interfaces, which allow operation without prior knowledge, are of great importance, especially for stressed teams. The intuitive operation of robot systems with heterogeneous hardware architecture represents an extraordinary challenge for commissioning and operation by untrained personnel. The user (head of operations) is supported in the respective task by relevant information (e.g. dynamic display of parameters, insertion of objects such as hydrants, emergency exit) or the representation of the recorded environment in 3D, see Figure 6 and 7. In the supplementary mode, operating data from the robot system can be displayed. For the representation and generation of robot and sensor models, ROS offers the Unified Robot Description Format (URDF), an XML format, which enables the use of the visualization tool RVIZ and the GAZEBO simulation environment. The URDF model therefore makes it possible to display the carrier platform with the modules used, see Figure 5.

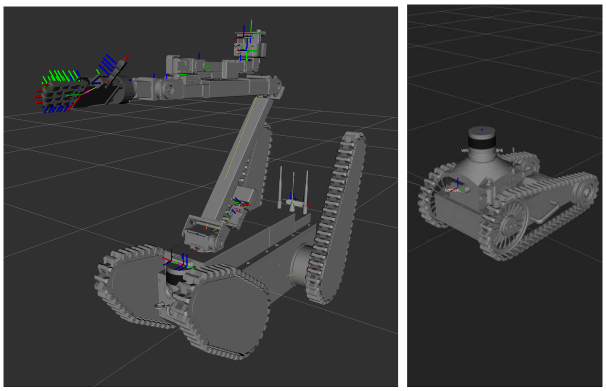

Fig. 5. Robot visualization as URDF Model

IV. EXPERIMENTS

Today, companies can choose from a large portfolio of transport and robot systems to perform complex tasks. A multi-sensor system is fundamental for automated operation and should ideally be capable of being integrated into any platform. The sophisticated application of sensor technology forms the basis for an innovative concept for analyzing and understanding scenes. In particular the use of cameras, LIDAR, radar and ultrasound sensors makes it possible to implement and further develop promising approaches of a combined 2D/3D environment analysis, as congruent depth information is available in addition to intensity and color information.

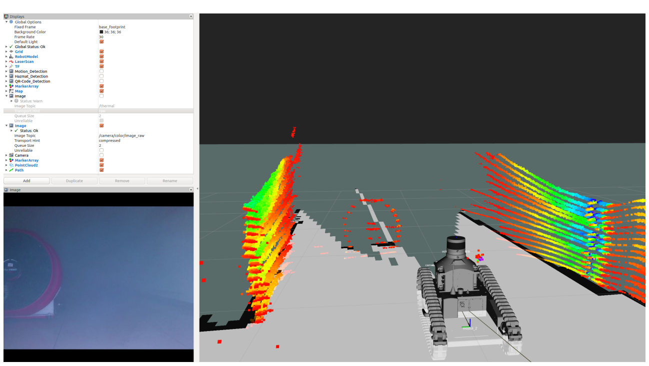

Fig. 6. Rescue robot MARK in real-life fire exercise

Figure 6 and 7 show two different applications with different robot systems equipped with different modules. Figure 6 shows the robot with a sensor module for exploration with LiDAR and RGBD camera, whereas Figure 7 shows a rescue robot equipped with a manipulator arm and using a stereo camera for 3D mapping and a 360-degree camera for live streaming.

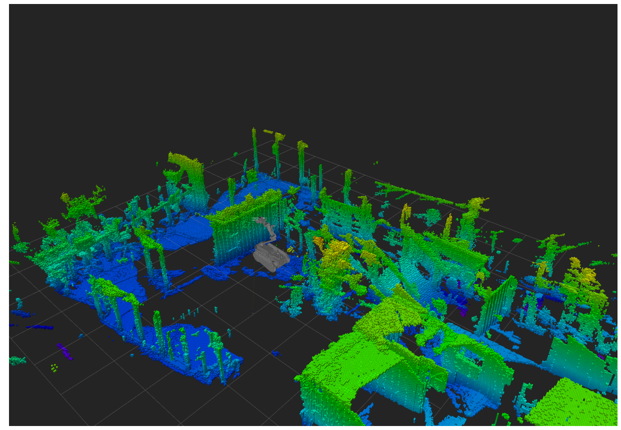

Fig. 7. Rescue robot COBRA in indoor laboratory

The entire system is modular in software and hardware so that it can be quickly assembled and integrated into any robot and vehicle platform. Fail-safe, fail-operational behavior and robust sensor fusion based on multi-modal sensor characteristics are therefore investigated in order to retain, certain functions even after a critical fault or sensor failure. The ability to tolerate systems, hardware and software, errors and failures is becoming increasingly important. A modular software framework is developed, which includes the following features:

- Sensor fusion: Fusion of an arbitrary number of sensors which do not restrict the number of input sources in order to tolerate failures and allow operation under different environmental conditions (e.g. weather).
- Sensor error and fail-operation behaviour: In the event of a sensor failure, the operational level of the platform should be adapted accordingly. This requires safeguarded concepts for basic functions (continuous pose estimation, etc.) to enable fallback modes like safe retrieval.
- Adaptive and situation-aware sensing concept: The sensor system recognizes the type of environment its operating in and adapts the sensor concept to the conditions in order to save for example energy and computing power on a mobile platform.

In contrast to this, improved assistance and autonomous capabilities promise to decrease remote human operator workload and increase the reliability of USAR robotic systems. Dynamic autonomy would be a significant advance for search and rescue robots, but is not straightforward to implement. Because of the complexity of the human factor and the need for the robot to be able to assess the level of danger it poses before it becomes irretrievably trapped or damaged. The complexity of transport and work processes in a dynamic environment and manipulation by the system itself makes tasks like sensor fusion and mapping especially challenging. In many applications there is not enough information from the environment, so 3D LIDAR, visual and telemetry data are required from the robot. Autonomous robots require an integrated system of efficient image processing, laser-based

3D SLAM, telemetry aggregation for robust traversability analysis, and cost-optimized path planning. Due to the modularity, LIDAR and/or visual based SLAM algorithms were tested independently. The robots were configured to the application in a very short time, making it easier to handle and prepare the entire system. The modular payload concept was presented and successfully implemented, especially in the Zwentendorf nuclear power plant. Extensive field tests were carried out in real scenarios as well as in the RoboCup Rescue League to verify the flexibility and modularity of the system and to generate sufficient test and training data. The demonstration of the system is primarily carried out according to the standard test methods for rescue robots.

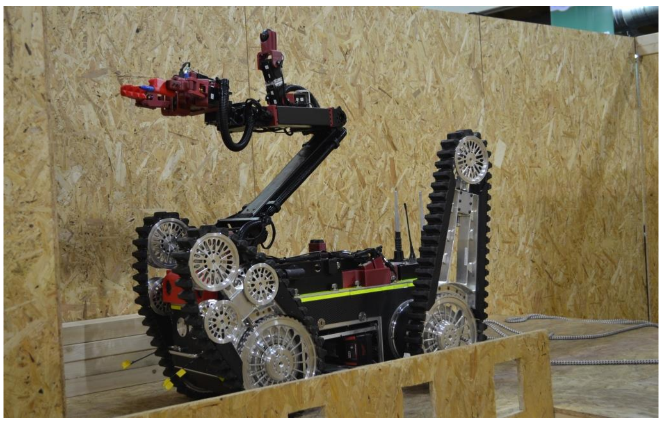

Fig. 8. Rescue robot COBRA at Robocup German Open 2019

Incidents such as Fukushima, Mayak or Chernobyl as well as the decommissioning and dismantling of old nuclear facilities (e.g. Murmansk) have taught us that the use of robotics. The concept was also tested at the new robotics competition, called ENRICH, see figure 9, which is the world's first and only robotics study that provides pure and unadulterated scenarios for testing hazardous materials and a complete incident response. It includes the search for real radiation sources, mapping difficult environments and the manipulation of valves and search and rescue victims.

Fig. 9. Sensor configuration for exploration at AKW Zwentendorf

V. CONCLUSIONS

The aim of this paper was to develop a payload concept with a plug-and-play approach to be used as a modular and flexible unit. This shall reduce the effort for system integration and sensor calibrating significantly and provide a customized perception of the environment during certain work processes. A controller unit for an automated utility platform will guarantee an efficient and safe bi-directional communication between the advanced systems for localization, mapping and navigation and the vehicle control components responsible for fundamental function like steering, braking and acceleration. Furthermore, this component shall provide information about the vehicle status and perform sanity checks that are essential for operational safety. Based on the developed components and concepts the field of application for mobile robots and automated utility platforms will expand significantly. Due to the utility platform concept, there are numbers of potential applications such as:

- Road cleaning (sweeping)
- mulching / cutting of green areas
- snow ploughing
- transportation
- road washing etc.

Those tasks are currently performed mainly by manned vehicles which are equipped with special tools.

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