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Autonomous systems for maintenance tasks - requirements and design of a control architecture

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Abstract

The technological change of the maintenance process from reactive to preventive methods correlates with the awareness, that maintenance is not only a cost factor but a business process, which is part of the added value of a company. The automation of maintenance tasks allows to plan the operation optimally and fast. This creates a significant economic advantage for the manufacturing industry and is the opportunity for autonomous systems to show their potential. The following work gives an introduction into the possibilities to automate the maintenance process, suggestions and a probable concept architecture for automated services and maintenance.

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Keywords: Automated maintenance; condition monitoring; autonomous systems; control architecture

Nomenclature

$\Sigma_{FFC}, \Sigma_{FFB}$; Σ_R, Σ_F:	Feedforward and Feedback Controller; Reference and Faulty System
$\mathcal{RCL}$; $\mathcal{D}$; $\mathcal{AM}$; $\mathcal{I}$; $\mathcal{S}$:	Reconfiguration Law; Diagnosis; Autarkic Module; Interface; Service
$\mathcal{SP}$; $\mathcal{HM}$; τ; λ:	Skill Primitive; Hybrid Move; Tool Command; Exit Condition

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1. Introduction

In highly automated and dynamic production processes the availability of the plant plays a crucial role, especially in regard to economic goals. Here maintenance is undergoing continuous changes, in order to meet the increasing boundary conditions. From a historical point of view, up to the year 1951 maintenance measures were only undertaken in case of a breakdown of a subsystem or the entire plant, before further preventive methods and in 1969 the Total Productive Maintenance (TPM) and the Reliability Centered Maintenance (RCM) have been developed [1]. This restructuring process correlates with the understanding that maintenance is no longer a mere cost factor but a cross-company business process which is an active part of the company's added value [2]. The process of change can be divided into three generations according to [3, 4] see Figure 1.

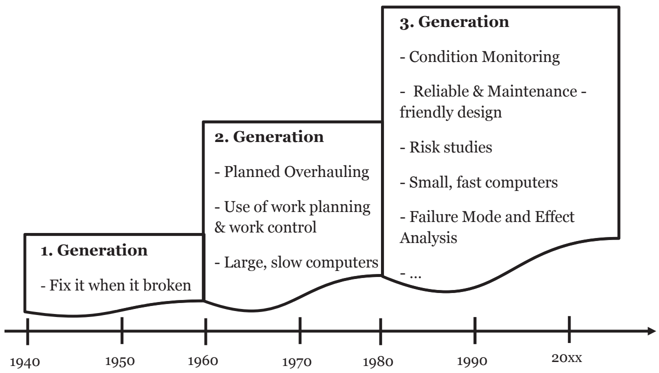

Fig. 1. Change of developments in the maintenance [3, 4].

It appears to be problematic that the increased automation of production systems results in a higher complexity and consequently to the need for more specific knowhow in order to understand the plant. In the course of different investigations of the operational behavior of complex production systems it was diagnosed that their availability is severely reduced with a higher degree of complexity [5]. Analyses have shown that approximately 30– 40% of the maintenance time is spent for the time it takes the maintenance technician to go to the location of the breakdown [6]. This is frequently caused by inadequate tools and fixed processes for coordinating the maintenance staff, especially in case of decentralized structures [7]. Also the same failure is more likely to reoccur than a totally new one [6]. The result is a considerable potential for optimization which can be achieved on the basis of flexible automation technology solutions.

In order to be able to produce in the future products in compliance with the cost pressure in high-wage countries, intelligent and flexible methods for automated maintenance tasks must be examined further. Establishing these methods in industrial applications could induce the beginning of the fourth generation in maintenance history. The following paper gives a comprehensive overview of current methods for maintenance automation and shows the existing connections and challenges. Further the schematic design of the required instances based on an information model will be discussed which are needed for the generation of automated service and maintenance sequences.

2. Method for Automated Maintenance

According to DIN 31051 [8] maintenance is divided into the categories service, inspection, maintenance and improvement of the plant. These measures can help to achieve a security-compliant operation as well as a minimum probability of fault and failure when the mechanisms are correctly implemented. That the process state corresponds with the desired state of the system, not only static and cyclic recurring service work (adjusting, exchanging, lubricating, …) has to be done, but dynamic and frequently non-deterministic failures have to be identified and eliminated. In order to be able to deal with this challenge, the typical failure patterns will be examined in more detail.

2.1. Failure Patterns in Mechatronic Systems

Nowadays, modern production systems are mostly designed as mechatronic systems. The components of such a system consist of the subsystems actuators, sensors and process elements, whereas these are composed of various disciplines from electrical engineering, computer science and mechanical engineering. The combination of different domains generally, leads to several patterns which are shown in Table 1.

Table 1. Fault characteristic in mechatronic systems [9].

Type of Faults		**Domain**			
		Mechanic	Electric	Electronic	Software
Form	systematic	●	○	●	●
	random	○	●	●	○
Time Behavior	permanent	○	○	●	●
	transient	●	●	●	○
	intermittend	○	●	●	●
	noise	○	●	●	○
	drift	●	●	●	○
Extent	local	●	●	●	●
	global	○	○	●	●

● Yes ○ No

The table above classifies the domain-specific patterns of occurrence. It shows the time sequence of a failure event as well as the extent of damage that can be local or global. According to [10] the faults are divided into inherent, non-inherent and physical faults.

Physical faults are caused by physical or chemical effects (wear and tear, age, etc.) whereas inherent faults already exist in the beginning of the operation and non-inherent only after the startup of the system [11]. The fault event can be basically divided into “big” and “small” faults. Small faults only change the system parameters, whereas big faults change the structure (actuator, process component or sensor breakdown) [12].

In the following sections methods will be described which permit automated maintenance.

2.2. Automated Fault-Diagnosis Methods

The inspection of the system includes monitoring (observation) of the machine or process status and the deduction of anomalies compared to the desired behavior. According to [13] the machine or plant diagnosis can be divided into the groups:

- Observation by the machine user (sensory perception and classification based on experience).
- Measuring equipment/testing method (mobile inspection).
- Test workpiece (information of the machine condition by measuring/ test workpieces).
- Additional sensors (permanently installed sensors in the plant).
- Drive-based diagnosis (signal interpretation or model-based methods).

Basically all points are suitable for automation, except for the first one. The process for fault-diagnosis can be divided into three steps [14], according to Figure 2. Fault-detection serves for the identification of deviations of certain process variables from the nominal operating status.

Further classification is done during fault-isolation, whilst fault-identification determines the size and extent of the fault. Meanwhile a considerable number of methods and procedures for fault-diagnosis have been developed that also frequently are employed in the industrial production.

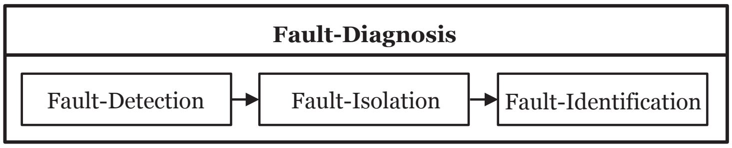

Fig. 2. Steps of fault-diagnosis.

Process-integrated Diagnostic Systems

With the dissemination of condition-based maintenance more and more integrated diagnostic systems are employed. According to [15] the methods for integrated fault detection can be divided into the following basic groups:

- **Limit value monitoring** (tolerances) and **plausibility check** (areas) of individual signals.
- **Signal model-based methods** for individual periodic and stochastic signals.
- **Process model-based methods** for two and multiple signals.

Here limit value monitoring presents an easy possibility to record deviations from normal behavior. Thus exceeding a defined interval limit or the observation of trends over time indicates an abnormal behavior. One example is temperature monitoring in electric drive systems. Therefore you need for each symptom a sensor, which is a real disadvantage and not a practical way to detect multiple faults. On the other hand, there is a group of fault detection principles that is also suitable for the evaluation of multiple signals. Here especially process model-based methods are looked at, since they basically present the most efficient methods for fault-diagnosis [16]. Frequently parity equations or parameter estimators as well as state observers are used, in case of non-negligible process and/or sensor noise state estimators (Kalman-Filters). The symptoms then are parameter changes, residues between process model and process output variables or changes of internal state variables [17]. Each system has its advantages and disadvantages, so parity equations and state observers are especially suited for additive faults under real-time requirements, whereas parameter estimators are mostly used for multiplicative faults [17, 18]. After the fault-detection follows the isolation and identification so that the type of fault and also the component involved can be determined. For this purpose usually classification methods from pattern recognition, statistics and artificial intelligence or interference technologies like fuzzy logic are applied [9]. There are numerous examples of applications, such as the use of Self Organizing Map (SOM) for online diagnosis in automation systems [19] or conclusions in regard to different types of faults, based on the measurement of gear vibrations by the use of Hidden Markov Models (HMM) [20]. Table 2 shows the specific characteristics of the individual diagnostic methods and gives a comparison. Chapter 2.3 will deal with the application of mobile diagnosis.

In summary there are many efficient algorithms for diagnostic tasks available, which have their origin in disciplines of the signal and control theory as well as in artificial intelligence. In spite of the efficiency of model-based approaches, most industrial condition monitoring systems work with simple signal analyses [18]. This is primarily due to the increasing complexity and heterogeneity of the systems and also those effects of uncertainties, disturbances and noise which need to be considered already in the design phase, because they have a negative impact on the diagnostic results [21]. Just as problematic as the long development time is the required expertise which is essential for the design of model-based diagnostic systems. Another point of criticism is that current diagnostic systems feature a modular design, but nevertheless they cannot be used universally. However, in view of the relatively short market cycles of today's products and assembly systems, the adaptability of the systems must be assured [22].

The previous chapter has shown that already a wide variety of methods for the automated inspection is available.

In view of the increasing autonomy of production plants, the next useful step will be the provision of methods that allow the production system to go back to its optimal operating condition or to carry out cyclically recurring maintenance tasks.

Table 2. Comparison of fault-diagnosis methods.

Properties		**Fault-Diagnosis Method**			
		Limit/ Trend monitoring	Signal Model	Process Model	Mobile
Design/ Integration	Additional Sensors	●	◐	○	●
	Complexity	○	◐	●	◐
	Expertise	○	◐	●	◐
	Modularity	○	◐	◐	●
	Invasive	●	○	○	◐
Operational Characteristics	Quality of Classification	○	◐	●	◐
	Detection Time	●	◐	○	●
	Detecting small Changes	○	◐	●	○
	Real-time capable	●	●	●	○
	Online	●	●	●	○
	Disturbance fragile	○	◐	◐	○
	Multiple Signals	○	◐	●	○

● Yes/High ◐ Neutral/Mid ○ No/Low

2.3. Automated Maintenance and Repair

Integrated Maintenance Systems

Often the objective is, to continue operating a machine or plant with consistent product quality up to a scheduled break, under changing system behavior. For this purpose the systematics of the fault-tolerant control (FTC) is a possible solution.

The term FTC refers to the adaptation or reconfiguration of the process control (feedforward/feedback) $\Sigma_{\mathrm{FFC}}/\Sigma_{\mathrm{FBC}}$ so that the required dynamic system behaviour can be retained. Based on the diagnosis $\mathcal{D}$ a general reconfiguration law $\mathcal{RCL}(\mathcal{D})$ needs to be computed, so that

$$\Sigma_{\mathrm{FFC}}, \Sigma_{\mathrm{FBC}}: \Sigma_{\mathrm{F}} \mapsto \Sigma_{\mathrm{R}}, \text{where } \Sigma_{\mathrm{FFC}}(\mathcal{RCL}) \wedge \Sigma_{\mathrm{FBC}}(\mathcal{RCL}). \quad (1)$$

With parameter changes (small faults) the use of adaptive control systems [23, 24] is particularly suitable for this. But also for structural faults (big faults) methods have been developed [12, 25, 26] for which the adaptive approach fails. Here a distinction is made between sensor and actuator faults. The basic idea in case of sensor faults is that the physical sensor can be replaced by a reduced observer, provided that the relevant state is observable, of course. For actuator faults the principle of the virtual actuator is introduced which combines the impact of several remaining actuators in a way that they replace the failed actuator [12].

Such redundancies or the existence of a number of actuators presenting a linear combination of the failed actuator cannot be expected in production plants, however. Due to economic factors (design costs versus benefit) the application of such precautions in production systems is only useful in terms of safety or in special applications and therefore this will not be considered any further.

Autonomous Systems for Maintenance

Besides the application of integrated systems there is also the possibility of using mobile maintaining systems. The automation of mobile inspection tasks is possible using autonomous robot systems. The employment of autonomous systems is primarily useful when permanent monitoring is too costly or structurally not feasible. Depending on the application, the robot system needs to be equipped with additional sensors like infrared thermography cameras, vibration measurement systems or tools for repair.

Traditionally these mostly teleoperating systems were used in risky and dangerous application scenarios that are inaccessible for humans, like in the handling of radioactive material or for military purposes [27, 28]. Mobile robot systems are widely used for the inspection of power supply systems. First prototypes enabled a remote-controlled navigation in energy transmission networks and the inspection for damages of power supply lines by means of eddy current test [29]. Subsequent developments allowed a semi-autonomous navigation [30] including the repair of broken strands with special clamps [31]. Further robot systems are found in the area of sewer cleaning, e.g. MakroPLUS [32], which navigates autonomously in sewer tunnels and performs measuring and cleaning tasks. Another example is the inspection and cleaning of boilers in thermal power plants [33].

Autonomous robot systems are also used increasingly in more complex environments like process plants [34, 35] and material flow systems [36, 37]. The maintenance robot for material flow systems can navigate autonomously within the plant with the help of the plant model and sensor-based path detection [36]. Then the robot performs mainly inspection tasks like vibration measurements, temperature measurements or optical inspections [37].


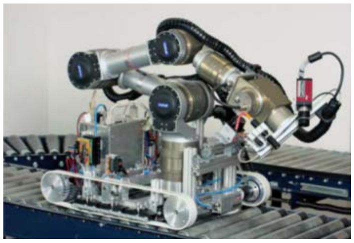

Fig. 3. Inspection of Power Supply Systems (Expliner) [30] (left); Autonomous Robot for Material Flow System [36] (right.

For complex maintenance and repair tasks there are no systems known yet. The following chapter is to describe a basic design of a control architecture which respects the requirements to automate maintenance missions. The framework based on a topological model of the production process which allows integrating the necessary information. So it is possible to close the existing gap referred to the state of the art.

3. Control Architecture for an Autonomous Maintenance System

Further an adequate system architecture is introduced which maps the entire functional chain of the maintenance process. From this follows the abstraction of the production so that a topological data model can be generated. Based on this, the structure of the diagnostic unit and the control of the autonomous maintenance robot are shown.

Topology Model Production System (TMPS)

The efficient planning and execution of manipulation sequences of the autonomous maintenance robot, needs prior knowledge about the environment, for example a broken function unit has to be changed in the production system. By abstraction, the diagnosis can made be easier. Also is it suitable to establish an instruction set for fault cancellation. Thus the option is given also in case of complex production systems to design diagnostic algorithms for individual modular production units and to connect these to the overall system. For this purpose the individual components of the production system needs to be encapsulated. By selecting adapted system boundaries the number of interfaces $\mathcal{I}$ can be reduced and thus the concept of the autarkic modules is introduced [38]. Autarkic modules $\mathcal{AM}$ should consequently present the smallest exchangeable function unit in a production system and can provide a service $\mathcal{S}$. Autarkic modules are defined as follows:

$$\mathcal{AM} \coloneqq \langle \Sigma_{\mathrm{Control}}, \mathcal{I}, {}^{(\mathrm{m})}_{\mathrm{n}}\mathcal{S} \rangle. \quad (2)$$

An autarkic module can contain actuators, process components (e.g. mechanical connections) as well as sensors, whereas these are coordinated by a control.

$$\Sigma_{\mathrm{Control}} \in \{\Sigma_{\mathrm{Acutator}}, \Sigma_{\mathrm{Process}}, \Sigma_{\mathrm{Sensor}}\}. \quad (3)$$

An interface $\mathcal{I}$ represents the complete mechanical connection of an autarkic model with its environment. Here $\mathcal{J}_{\mathrm{int}} \ni \{\imath_{\mathrm{int,1}}, \imath_{\mathrm{int,2}}, \dots, \imath_{\mathrm{int,k}}\}$ presents an internal interface with several components $\imath_{\mathrm{int,l}}$ and a connection from an autarkic module $\mathcal{AM}_{\mathrm{m}}$ to $\mathcal{AM}_{\mathrm{n}}$ contain ${}^{(\mathrm{m})}_{\mathrm{n}}\mathcal{I} \ni \left\{{}^{(\mathrm{m})}_{\mathrm{n}}\imath_1, {}^{(\mathrm{m})}_{\mathrm{n}}\imath_2, \dots, {}^{(\mathrm{m})}_{\mathrm{n}}\imath_{\mathrm{k}}\right\}$ where ${}^{(\mathrm{m})}_{\mathrm{n}}\imath_{\mathrm{l}}$ represents the numerous components, thus

$$\mathcal{I} \coloneqq \langle \mathcal{J}_{\mathrm{int}}, {}^{(\mathrm{m})}_{\mathrm{n}}\mathcal{I} \rangle. \quad (4)$$

The connection of the components that provide an interface can be specified according to [43] as an AND/OR-Graph. Here costs are assigned to the edges E which are evaluated according to different criteria [44]. The vertices V are assigned to the elements to be solved from the quantity $\mathcal{I}$, hence $\mathrm{V} \subseteq \mathcal{I}$. So it is possible to describe the planning of a Maintenance or Repair Sequence (MRS) as a searching problem and do the exchange of a broken module (disassembly and assembly). The computed MRS can be stored as a digraph $\mathrm{G_{MRS}}(\mathrm{V}, \mathrm{E})$ and used from the autonomous maintenance robot (AMR) to do the mission.

A service ${}^{(\mathrm{m})}_{\mathrm{n}}\mathcal{S}$ is the appropriation from one or more functions, that $\mathcal{AM}_{\mathrm{m}}$ provides to $\mathcal{AM}_{\mathrm{n}}$. An example is that a production unit transport a workpiece from m to n.

$${}^{(\mathrm{m})}_{\mathrm{n}}\mathcal{S} \in \{\mathcal{S}_1, \mathcal{S}_2, \dots, \mathcal{S}_{\mathrm{k}}\}. \quad (5)$$

Due to the formal description an adequate topological knowledge base can be established. For the practical implementation of complex production structures the Automation Markup Language (AML) [45] can be used.

Architecture Diagnosis System (ADS)

Chapter 2.2 demonstrated that extensive methods for automated diagnostics already exist. The problem of frequently missing expertise also pointed out. This is needed for fault-isolation and fault-identification. This problem can be solved by providing decentralized services, according to [42]. For this the individual autarkic module $\mathcal{AM}$ is provided with a diagnostic function $\widehat{\mathcal{AM}}$. The greatest benefit of outsourcing the diagnostic functions is the possibility to collect information from similar components of globally distributed production systems and to establish an efficient knowledge base. For this the input and output data are taken from the real production system and passed into a distributed system. Higher plant availability could be achieved if fault symptoms are classified more effectively based on knowledge components. If a damage is identified the control of the maintenance robot is informed in a diagnostic message $\mathcal{D}$ about an error and the measures to be taken. Thus the functions required for the robot application can be deducted. The diagnostic message could be defined as follows

$$\mathcal{D} \coloneqq \langle \mathcal{AM}_{\mathrm{i}}, \mathrm{G_{WDS}}(\mathrm{V}, \mathrm{E}) \rangle. \quad (6)$$

Control Architecture of Autonomous Maintenance Robot (CAAMR)

For the control of autonomous robots various paradigms have been developed in the past. Basically a distinction is made between deliberative (sense-plan-act) and reactive architectures.

Deliberative architectures process sensor data, update the internal world model on the basis of the gained information, plan the most expedient action and transmit this to the actuator system. Reactive architectures, however, do not have a world model and map the sensor inputs directly to the actuators. Calculations between sensor input and action are permitted as long as the system reacts “fast enough” to the required situation [41]. Whereas with deliberative strategies primarily the long planning phase can be a disadvantage, the problem with reactive architectures is oftentimes that long-term objectives cannot be pursued. Figure 4 illustrates the schematic structure of the autonomous maintenance architecture with all required components. Here the ADS provide the diagnosis algorithms scaled to the manufacturing process. The ADS can send the diagnosis $\mathcal{D}$ to the ARS controller which build the MRS and match this to the skill primitives, see next paragraph.

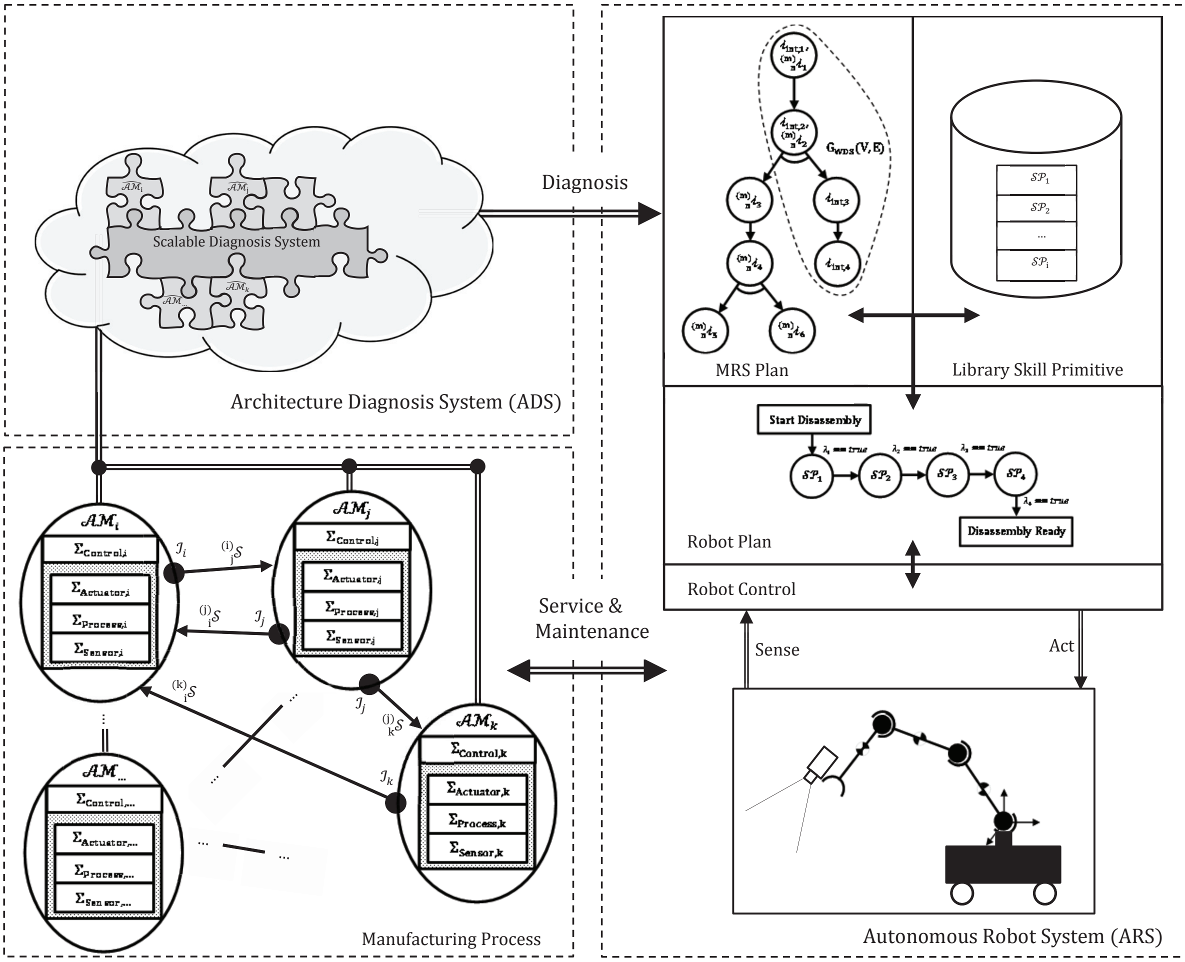

Fig. 4. Autonomous maintenance architecture.

Due to the benefits and disadvantages of the individual systems, the application of hybrid multi-layer architectures has prevailed in practice, because they combine both control paradigms [40]. Based on this architecture a concept is to be found which allows a modular robot control.

To follow the plan gained from the TMPS a transformation in robot-specific tasks has to be executed that can compensate environmental uncertainties by the use of sensors. For this purpose the paradigm of skill primitive is suitable according to [39]. Skill primitives present the smallest step of a robotic task, where a task can be fulfilled in a feedforward- or feedback-controlled way. A skill primitive $\mathcal{SP}$ is to be defined as a triple with

$$\mathcal{SP} \coloneqq \langle \mathcal{HM}, \tau, \lambda \rangle. \tag{7}$$

Here the hybrid move $\mathcal{HM}$ is the determination of the cartesian robot motion in a specified coordinate system. This can be monitored via the definition of sensor functions by activating a force control for example. By applying sensor-guided actions a reactive adaption to the environment is possible.

Due to the tool command τ, tools are defined, addressed and applied. One example would be addressing a *"Gripper"* with the command *"Close Gripper"*.

The completion of a skill primitive is indicated by the exit condition λ if the status true is reached. For this the sensor inputs S are mapped to a Boolean value so that

$$\lambda: S_1 \times S_2 \times \ldots \times S_i \mapsto \{\text{true}, \text{false}\}. \quad (8)$$

In the robot control the MRS can be implemented directly on skill primitive network. The required skill primitives can be preconfigured and inserted from a library. It is also possible that the skill primitives could be shared between the robots thru a distributed system.

4. Summary and Outlook

After a detailed summary of the currently existing methods and systems, a fundamental concept for planning and control of automated service and maintenance actions was demonstrated. This permits a modular approach for implementing diagnostic as well as robot control sequences. Due to the distributed architecture the diagnostic system can collect data from different production facilities of similar autarkic modules, which are combined in a knowledge base. With the use of machine learning methods (Support Vector Machines) a rapid classification of fault symptoms becomes possible. By introducing skill primitives according to [39] modular control architecture for the AMR can be established which can react robustly to uncertainties because of the sensor observed control.

In the future skill primitives have to be generated dynamically based on camera and CAD data. For this purpose, specific features of the interface elements are stored in a database and can be classified. Further it will be investigated how far a disassembly can be carried out without a plan. Here the dismantling of the interface is done incrementally. The following mounting procedure is then generated from the previous knowledge about the disassembly.

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