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STRUCTURE AND WORKING MODES OF THE INTELLIGENT ADVISER MODULE

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Abstract

This paper describes the Intelligent Adviser Module (IAM) as a decision making support tool for the system operator in Bionic Assembly System (BAS). The efficiency of BAS depends on many parameters and also on the ability of the system operator to reach quality decisions in good time. The main target of the control system is to reach the highest machine utilization in the given working conditions. Working scenarios are realized with the execution of all activities which are needed to assemble a continuous stream of products. Continuous stream of products is made with assembly orders. One assembly order means to assemble one run of product. In a normal working mode there is always a small difference between planned and realized working scenarios. This difference is compensated by the automatic control system. If the difference increases beyond the automatic control system's ability to compensate it, the system operator has to make decisions which bring the system back to a normal working mode, efficiently. Efficiency depends on the relation between the quality of the decisions and time needed to make them. Higher efficiency means higher quality of decision made in shorter time. The best way is to make decisions while the machines are working. This is not always possible and in that case the machines must wait for the decision. Machine waiting is lost machine time. This has to be avoided or minimised. This time shortage brings stress to the system operator and forces him to make lower quality decisions. In this situation, the IAM offers a decision support in form of proposals. A working IAM prototype is developed, realized and analysed in predefined laboratory conditions. The analysis of the results show that the IAM is a promising operator decision support tool for complex assembly systems.

Keywords: Intelligent Adviser; Bionic Assembly System; hybrid control structure; expert systems; knowledge discovery

1. Introduction

Current product development is defined with increased product complexity, variety and shorter lifetime [1]. Modern assembly systems need to respond to these challenges through adaptability, efficiency and robustness. They need to be capable of assembling a large variety of products with high complexity within defined customer deadlines. As a result, the working scenarios are becoming more complex and the sophistication of the control structure is proportionally increasing [2].

As an answer, a Bionic Assembly System (BAS) concept based on task distribution, intelligence and self-organization is introduced [3]. It presents the next generation of hybrid assembly systems which combine two basic control structures and principles. First is centralized upper control system based on hierarchy and the second is the self-organizing control system based on heterarchy [4].

BAS is a human centric assembly system which promotes the integration of humans within the assembly process [5]. The main decision maker is the human system operator. The efficiency of the Bionic Assembly System depends on his limited ability to reach repetitive, high quality decisions in good time. Good time means that the machines are not waiting for his decision. Main goal is to achieve minimum lost machine time by avoiding standstills during assembly.

However, this introduces new challenges for the system operator. The system complexity, large amounts of data, distractions and disturbances have a high impact on his capabilities to run the entire system and to perform his tasks. In addition to that, as a human, he has limited physical and cognitive capacity to reach repetitive quality decisions over a long period of time [6]. He needs a decision support system which will support his decision making abilities. Such a system needs to be capable of replicating human intelligence, learning and thought processes. This is becoming possible thanks to the rapid development of information technologies (IT) and the introduction of Artificial Intelligence (AI) [7].

As an answer to these challenges, the Intelligent Manufacturing Systems (IMS) group from Vienna University of Technology has introduced the Intelligent Adviser Module (IAM) [8]. It is a decision support tool integrated as a part of the BAS control structure as shown in Fig. 1. On one side, the expert system platform of the IAM enables it to model and represent human knowledge. On the other side, it uses the recorded past system data for learning through knowledge extraction.

The knowledge extraction process was described in the previous paper [9]. It demonstrated how recorded past system data was used to identify a correlation between components from different suppliers and the quality of the final product. Once the results were evaluated, the new knowledge was specified in form of rules. This paper describes the IAM structure, its working modes, how new knowledge is imported into the KB and used to propose new solutions to the system operator.

2. Intelligent Adviser Module Structure

The final decisions have to be made exclusively by the system operator. The IAM needs to support him during the decision making process. The main concept is that the IAM learns and improves its accuracy over time. This is realized through the IAM structure and its integration within BAS. As a result of this integration, data can be collected and analysed and useful proposals can be presented to the system operator when he needs to make a decision. As shown in Fig. 2., the main IAM structure is composed from the following submodules:

- System Monitoring
- Knowledge Management
- Decision Support

2.1. System monitoring

Working scenarios are executed as a continuous stream of one or more parallel assembly orders. One assembly order means to assemble one run of product. The realization of working scenarios is tracked through real time system monitoring. The progress of this realization is determined from the analysis of the target and actual state of the system. If the difference starts to be critical, the IAM notifies the operator.

IAM is an integral part of the BAS control system and is connected to all other system components [8]. It serves as an information hub and as such it presents current system information to the system operator. This includes performance of the shop floor elements as well as the disturbances that can occur, resource levels and status of assembly order completion. If there is a critical error or a malfunction, an audio-visual notification is sent to the operator.

Notifications can be triggered via:

- Threshold values (minimum, average, maximum) – This kind of notifications are based on measurements. They can be sent if the stock of resources is getting too low, if the duration of an operation is above a maximum scheduled time, if a robot's battery is almost depleted, etc.
- Boolean logic (yes / no, on / off) – These notifications can be sent according to a specific sensor readout. This can include if a station is shut down or turned on, if a robot is moving, if the shop floor operator is present at a specific position, quality control is good or bad etc.
- Trend predictions (incline, stagnation, decline) – Trend prediction notifications are based on measurements, data analysis and correlation functions. These methods are being successfully implemented in the prediction of tool breakage [10]. This enables the IAM to proactively warn the system operator before a failure occurs. As a result, the system operator can make decisions with which disturbances can be avoided and consequently increase the efficiency of the assembly system.

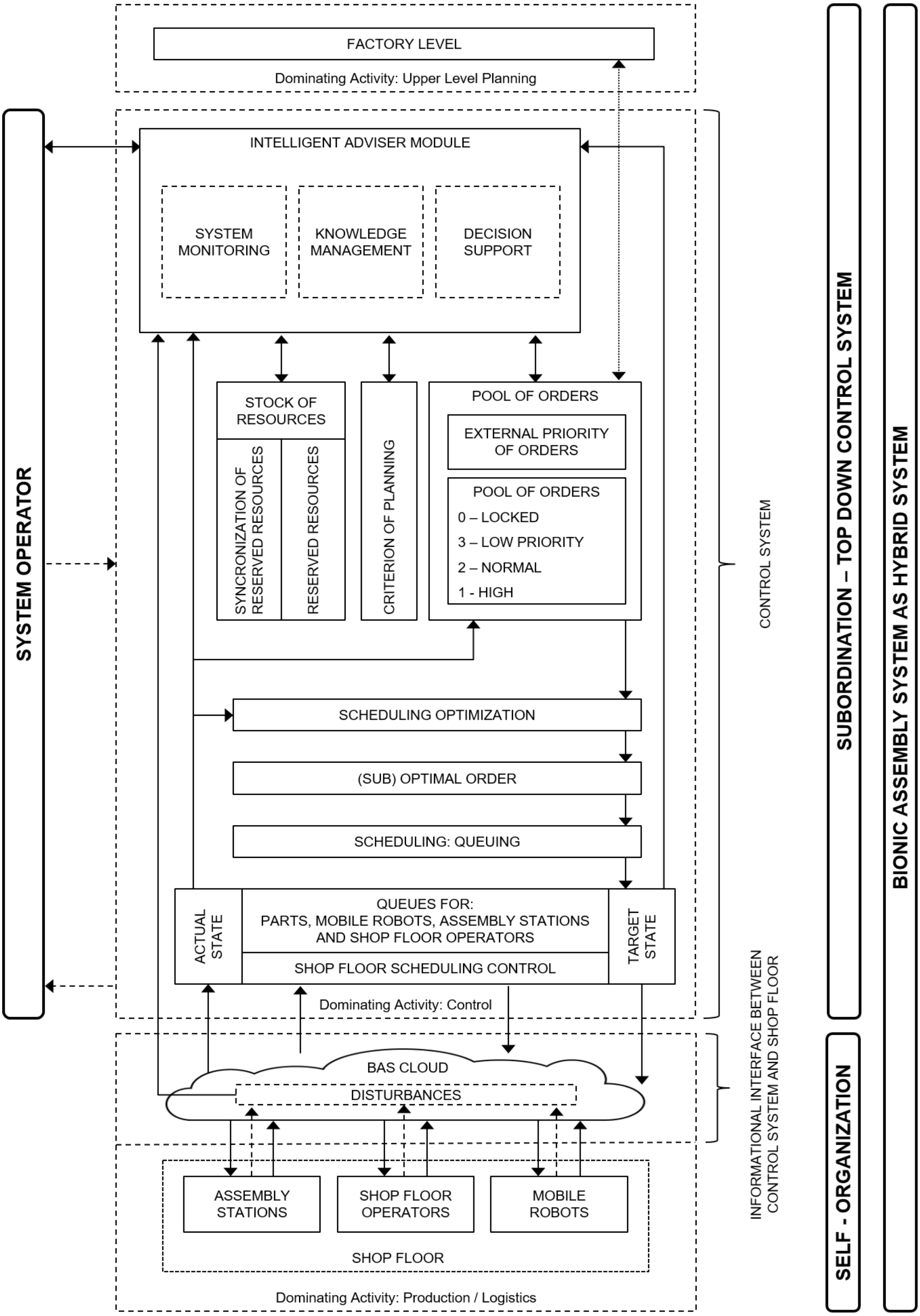

Fig. 1. Intelligent Adviser Module within BAS control structure

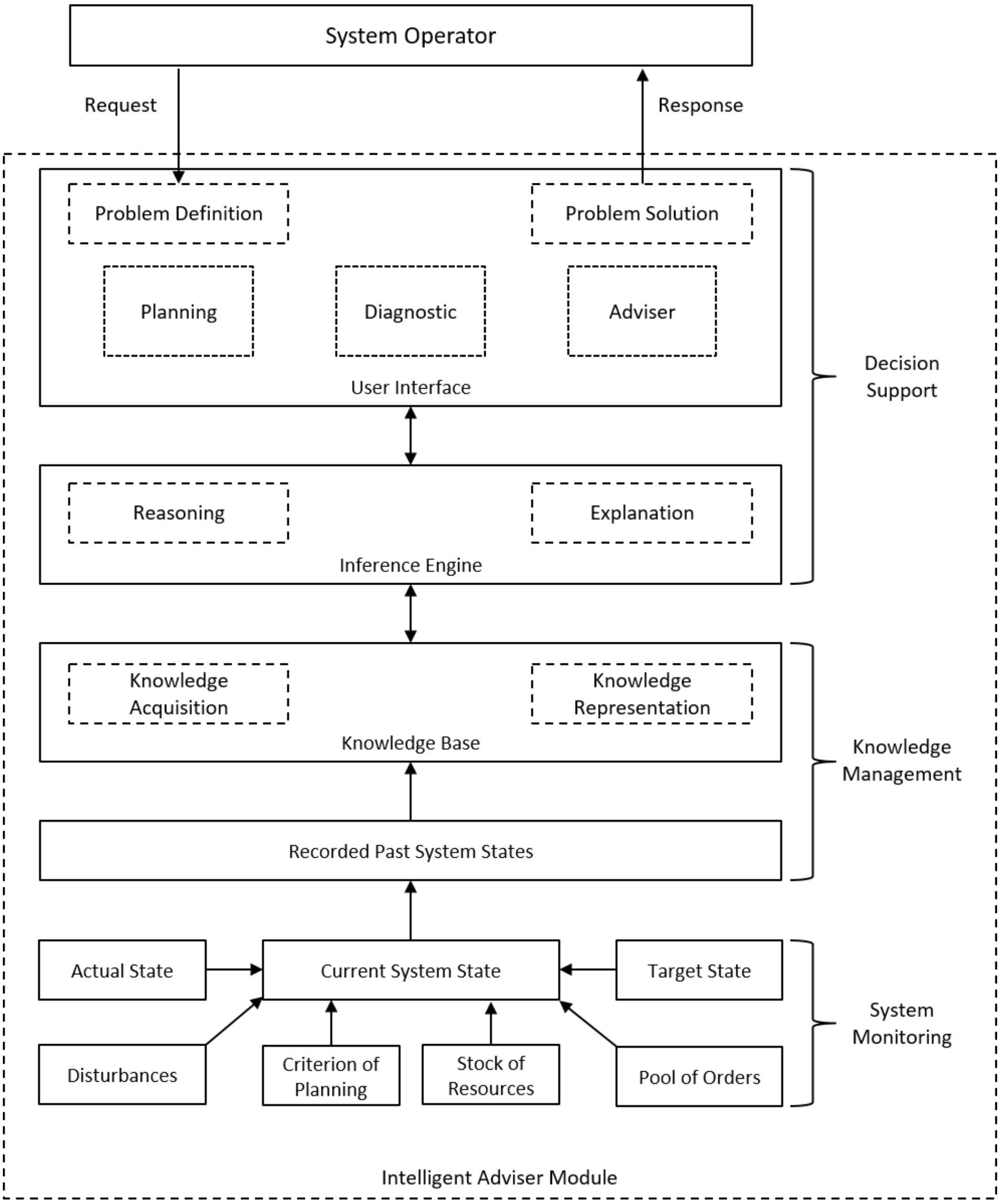

Fig. 2. Intelligent Adviser Module structure

2.2. Knowledge Management

The output from the IAM are proposals. The quality of these proposals have a direct influence on the system operator during his decision making process. He has to be able to reach quality decisions in good time. This can be achieved if a previously unknown correlation between predicting datasets (suppliers, hardware age or performance, process duration…) and target datasets (end product quality, breakdowns…) derived from past system data can be identified. In other words, the system needs to be able to acquire new knowledge based on data derived from the execution of past working scenarios.

Knowledge Management is based on:

- **Recorded Past System States** – System monitoring produces large amounts of data which is constantly recorded. This recorded data represents past system states and is the basis for the Knowledge Base (KB). The main information flow channel is between the control system and the shop floor. A real time exchange of information in both directions is taking place. Control system sends instructions, commands and data to people, machines and robots. They send feedback information about the realization and hardware status. The IAM receives all data from this communication channel and stores it within a database. This data consists out of measurements, quality reports, disturbance occurrences, robot travel times, operation times, external and internal resource tracking, status of orders, selection of orders based on specific criteria, past system operator decisions, etc.

- **Knowledge Base** –KB contains different knowledge types in a format which is understandable to a computer system. It uses Knowledge Representation (KR) methods to store facts, theories, rules, procedures, strategies as well as heuristics. The IAM is able to learn from past events through the Knowledge Acquisition (KA) process. This process consists of data preparation, exploration, modelling and evaluation. It is used to describe past events or to predict future system behaviour if a correlation between parameters is found. The quality of the KB improves over time as more and more data is accumulated. It is possible to identify the influence of particular causes on the overall results. The recorded data also contains the past system operator decisions in contrast to the past system states. This allows to extract his expert knowledge and to define expert decision rules which can be used in future. If there is a similar situation where a decision needs to be made, the IAM can quickly recognize it and make a proposal according to the past results. If the past decision from a system operator was satisfactory, it can be reused. On the other hand, if the decision he made had negative impact on the system performance, it can be shown as a warning to avoid similar negative decisions.

2.3. Decision Support

The IAM decision support is realized through the implementation of an expert system. It gives an ability to reason about the acquired knowledge from the KB. Once the KB has been defined, it is connected to the reasoning module also known as the Inference Engine or the Rule Interpreter. It is a computer algorithm which uses, acquires and manipulates knowledge in order to define a solution to a specific problem as well as asserting new knowledge back to the KB. It decides which rules to apply and resolves conflict situations when multiple rules are applicable to a particular case [11].

The inference engine in the IAM enables the following two capabilities:

a) Reasoning

Reasoning allows to reach conclusion based on facts and rules derived from the KB. It can be used for diagnostics or to identify problems. Reasoning knowledge can include [12]:

- Deduction: starts from a general theory based on wide range of facts, rules and principles and narrows it down to a specific conclusion
- Induction: starts from specific observations (measurements), identifies the existence of patterns or regularities and at the end defines a conclusion
- Classification: grouping concepts, ideas and objects into related categories
- Analogy: reaching conclusions after recognizing that two or more thing have specific characteristics in common. By analogy, if they have one, they can have more characteristics in common.

b) Explanation

The assembly process within BAS is very complex and it is hard to cover all scenarios and disturbances. One of IAM advantages is that it becomes more accurate as more data is accumulated. However, as with any other system, mistakes are possible. This can happen because its KB is incomplete or contains incorrect facts or rules. As a result, conclusions can be inaccurate.

This is why it is very important that the IAM can demonstrate the logic behind the reasoning. This is completed using the explanation capabilities of the inference engine.

During the decision making process, the system operator has several options when presented with a proposal:

- Acceptance – In this case the system operator accepts the IAM proposal without considering the its background reasoning logic. It can happen because of multiple reasons. This includes high stress situations, when he is not concentrated, when a decision is needed immediately, when his knowledge is not sufficient or simply when he agrees with the proposal.
- Inspection – If the system operator is not satisfied or suspects the validity of the proposal, he will inspect it using the explanation mechanism. It shows every step of the reasoning process through the graphical user interface. Presentation methods can include a text based report or a visual reasoning tree. The advantage of a rule based knowledge representation over procedural code is that it is much easier to present explanations to the system operator in a more natural and understandable way. This allows to clearly view which rules were fired and what new facts were asserted.
- Rejection – The system operator can reject proposals if he has enough knowledge about the specific problem or if he decides that the reasoning is flawed after performing an inspection. In either case, his decision is recorded for future reference. Based on his past decisions, new rules can be extracted from the recorded data and the inference engine reasoning improves.

3. Working modes

Functionality and efficiency are the two most important requirements of BAS. The main goal of the entire system is to achieve efficient processing of continuous stream of one or more parallel assembly orders. One assembly order means to assemble one run of product. Each product is assembled according to a defined sequence of operations. For every operation there is a group of machines which can complete them.

To ensure that BAS is working with the highest possible efficiency, it has to be organised so that the minimal sum of lost machine time is achieved. This can be accomplished through the organisation of the system according to the following secondary goals:

- Machines standstills are avoided by ensuring their uninterrupted work. To achieve this, every machine has to have the necessary NC programs, tools, workpieces and various other resources at their disposal at the right time.
- Machine setups should be as short as possible. Setup procedures should start without delay and all necessary resources have to be available at the right time.
- Removal of machine standstills. In case that a machine is not working, it has to be brought back to a working state as soon as possible or replaced if possible.

For this reason, target and the actual state of the system are monitored. There is always a difference between planned and realized working scenarios as shown in Fig. 3. System efficiency directly depends on this difference. Smaller difference means higher system efficiency and smaller number of minor disturbances. Depending on the size of the difference, there are three main working modes during the execution of BAS working scenarios: normal, fluctuating and emergency working mode.

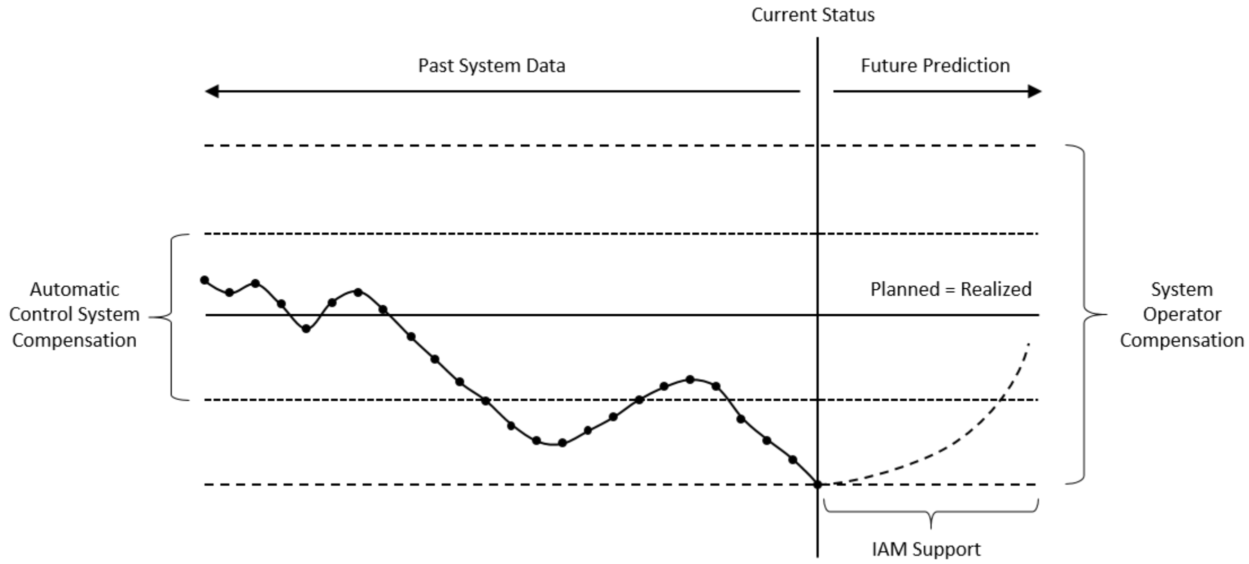

Fig. 3. Intelligent Adviser Module working modes

3.1 Normal working mode

Small differences between planned and realized working scenarios are compensated by the automatic control system and the self-organizing nature of the shop floor. In this mode, the entire assembly process is regulated without the intervention from the system operator. These small differences are caused by chance causes. They are negligible and inevitable variations which occur in random manner during assembly. Such variations cannot be anticipated, detected, identified or eliminated from practical or economic reasons [13].

Causes of small differences can include [14]:

- minor variations in operation start / end times
- mobile robot traveling times
- occasional failed quality control checks
- slight variations in raw material
- vibrations caused by operating hardware
- normal wear and tear
- computer latency
- minor imprecise shop floor operator actions
- working conditions (light, noise, temperature, humidity, dust, ventilation...)

For example, if a product during its assembly did not pass a quality control check, the system reroutes it to a repair station. However, a certain percentage of errors are non-reparable. In that case the automatic compensation system needs to ensure that the exact number of ordered products is completed. That means that the defective product is discarded and an automatic replacement order takes place. If there are multiple failed products it implies that there are more serious problems in the system. The automatic control system cannot compensate for it.

3.2 Fluctuating working mode

The automatic control system is limited. If the difference is increasing beyond its ability to compensate it, the system operator is notified to actively bring the system back to a normal working mode. The cause of these more serious differences are called assignable causes [15]. They result in a large amount of variations during assembly. They can be detected, identified and eliminated.

Fluctuating working mode can be caused by:
- Defective raw material
- Shop floor operator is absent or asleep
- Wrong equipment adjustment or calibration
- Defective mobile robots
- Machine malfunction
- Power fluctuation

In a fluctuating mode the system operator has enough time and ability to solve a simple problem. Simple problem means that it is relatively easy to diagnose and to determine a solution. Because assignable causes can be detected, the system operator uses the IAM to help him quickly determine what the problem could be and where it occurred. For example, an assembly station is waiting a long time because a mobile robot has a faulty wheel. When a new problem is detected, a Problem Record File (PRF) is created. It is registered with its ID which is composed from a timestamp (YY-MM-DD-HH:MM:SS) and an additional 4 digit identifier (####). PRF contains all the available data which includes times, status of involved hardware, sensor readouts, possible solutions (if applicable) etc. All this information is presented via menus, tables, graphs etc. to the system operator. He uses this information to investigate and make a decision. The applied solution as well as the final results are recorded in the PRF. In this case, after replacing the mobile robot with the faulty wheel, the waiting error was removed which means that the solution was successful. All this information can be useful to the system operator if a similar problem repeats.

3.3 Emergency working mode

Extreme differences between planned and realized working scenarios mean that there is a problem caused by multiple errors. In such an emergency working mode, the system operator does not have enough time or ability to make a decision. He uses the IAM as a decision support software which helps him to reach higher quality decisions in good time. Emergency working mode can be caused by previously described assignable causes. When these causes occur at the same time it can result with:
- Bad quality in an assembly run
- Inability to keep up with deadlines
- Multiple machine failures

Unlike in fluctuating working mode, the system operator does not have enough time to investigate and analyse all the options and navigate through multiple menus. He needs to be presented with the most important information which includes problem description, possible explanations and a solution. For this reason, he activates the adviser function. There are two ways how the IAM can output proposals: from KB history or through a dialog manager.

When a problem occurs, the KB history is searched in order to find any matches which could be used. There can be multiple matches. The system operator selects the option with the highest match percentage. He is then presented with the details which include the past problem description, causes, applied solution and the results. From this, the system operator decides if the proposal is applicable.

In case that there were no matches found in the KB history or if the system operator does not think that the presented options are applicable, he can activate the dialog manager. It serves as a problem solving interface between the IAM and the system operator. The exchange of information is performed like a conversation as shown in Fig. 4. This makes it more natural and intuitive for the system operator. The dialog manager was developed in CLIPS 6.3, which is an open source programming tool for building expert systems. The KB contains expert knowledge represented through complex rules functions and object [16]. Using the inference machine, KB and its expert knowledge the IAM performs reasoning in order to find a solution. The system operator answers the questions and follows the instructions. At the end, he is asked if the proposed solution solved the problem. If yes, it is recorded in the PRF. If not, other possibilities are tried until a solution is found or there are no more rules. This is the worst case scenario which is possible in young systems.

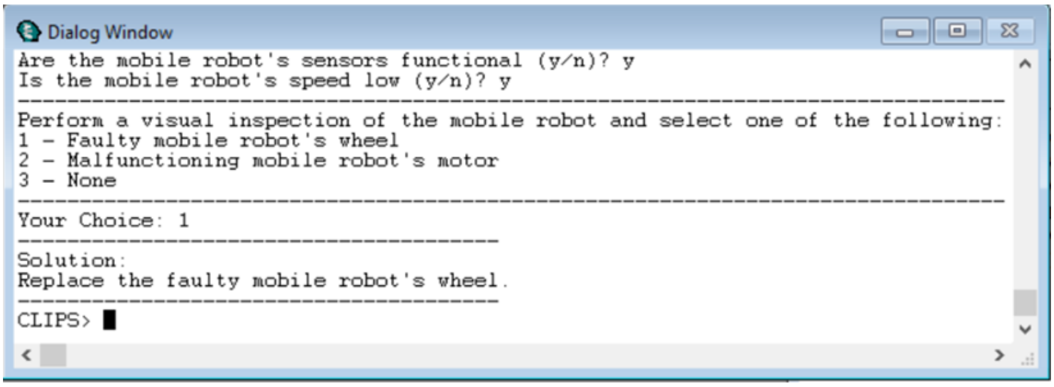

Fig. 4. IAM Dialog Manager – developed in CLIPS 6.3

4. Learning from past system data through Knowledge Record File

As stated, the KB contains knowledge from a specific domain. This knowledge is defined as rules which represent the expertise from human experts, troubleshooting manuals, domain specific facts etc. This is appropriate for hardware related problems, to solve malfunctions and for transferring general experiences of the domain expert into the KB.

The advantage of the IAM within BAS is that it is able to learn specific system related knowledge which is generated during the operation of the entire assembly system. This includes knowledge about events which have not occurred ever before and as such are very difficult or impossible to predict and include in the KB. These events represent the past BAS system states.

This example is a continuation of the knowledge acquisition procedure described in the previous paper [9]. The IAM has detected that there is a high number of specific products with unsatisfactory quality results. A new PRF has been created where all the facts are listed which includes involved assembly stations, shop floor operators, mobile robots, used components, their suppliers etc. The system operator is notified and he uses the dialog manager to solve the active product quality problem. He answers the questions and follows the instructions, but a solution is not found. The problem is very specific to the current execution of BAS working scenarios. The following message is shown to the system operator:

"Unable to determine the cause of problem.
The Knowledge Base needs to be updated."

To solve this, new knowledge needs to be imported. After the recorded past system data has been analysed, the best predictor has been identified with its matching set of new rules as shown in Table 1. This represents specific new knowledge based on past system data. The connection between the knowledge management and the decision support submodules is the Knowledge Record File (KRF) generator as shown in Fig .5. The main function of the KRF generator is to translate these new rules into a format which CLIPS can understand. A part of the KRF code for these new rules is shown in Table 2. Each time new knowledge is discovered and evaluated a new KRF is generated. Each KRF is also registered with its ID which is composed from a timestamp (YY-MM-DD-HH:MM:SS) and an additional 4 digit identifier (####).All these KR files are imported into the KB and the entire system becomes "smarter".

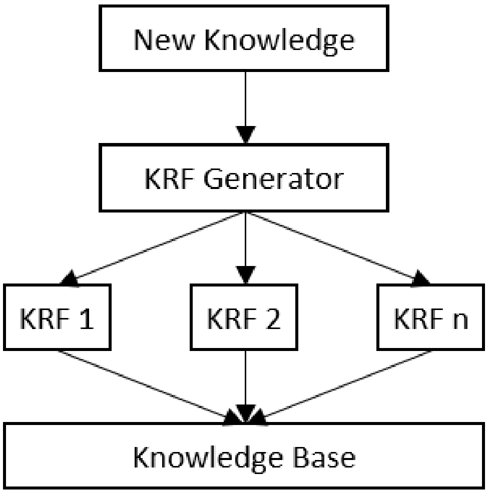

Fig. 5. Expanding the Knowledge Base with Knowledge Record Files

Timestamp_ID	**2016-11-19-16-01-29_340**		**New Rules**
Supplier ID	**product_quality**		
	OK	NO	
SUP_114	29	0	IF Supplier ID = SUP_114 THEN Quality = OK (29 OK > 0 NO)
SUP_442	72	4	IF Supplier ID = SUP_442 THEN Quality = OK (72 OK > 4 NO)
SUP_559	8	28	IF Supplier ID = SUP_559 THEN Quality = NO (8 OK < 28 NO)
SUP_746	57	2	IF Supplier ID = SUP_746 THEN Quality = OK (57 OK > 2 NO)

Table 1. Best predictor identified after Knowledge Acquisition (9)

Now, the new set of rules have been imported into the KB and is possible to go back to the example where the IAM reports that there is a problem with unsatisfactory quality results. The generated PRF among other data contains that the supplier of the used components was “SUP_559”. In this case, if the system operator selects the option to solve the active problem again, the following solution is displayed:

“The components are delivered by the supplier SUP_559.
Final product quality is unsatisfactory because the supplier SUP_559 is bringing subpar components.”

```
;==========================================================
; Intelligent Adviser Module for Bionic Assembly System
; Knowledge Record File: KRF_2016-11-19-16-01-29_340
;==========================================================

(defrule KRF_2016-11-19-16-01-29_340/SUP_559 "Supplier ID: SUP_559"
(SUP_559)
=>
(assert (solution ok))
(assert (product_quality_NO))
(printout t "The components are delivered by the supplier SUP_559." crlf)
(printout t "Final product quality is unsatisfactory because the supplier SUP_559 is bringing subpar components."
crlf
crlf))
...
```

Table 2. Part of the KRF code for CLIPS 6.3

5. Conclusion

A working prototype of the IAM was developed and analysed. The analysis results show that the IAM can be successfully integrated in the control system of BAS. The proposed IAM structure is designed to integrate system monitoring, data collection and knowledge discovery functions with a decision support expert system. Such integration takes advantage of large amounts of data generated during the execution of BAS working scenarios. The rule based method for knowledge representation gives promising results. The main advantage is the possibility to include predefined expert knowledge, facts and definitions with new system specific knowledge. This makes it possible for the quality of IAM proposals to constantly improve. When the IAM gives more precise proposals, the system operator can make better quality decisions in shorter time and avoid or minimise lost machine time. Further results demonstrate the IAM usability in all possible work flows which can occur in every day operation of BAS. It offers flexible levels of support according to varying difference between planned and realized working scenarios. This makes it possible for the system operator to select a working mode according to his wishes. Based on the results presented in this paper, future research will focus on the investigation of the IAM performance in real industry working scenarios. Main topics of research will include IAM stability, maintenance, optimization and general usability. Additionally, different methods of information exchange between the IAM and the system operator will be examined. One possible direction of further development is the implementation of speech recognition and voice assistant capabilities of the IAM. This could introduce new possibilities in the work flow of the system operator.

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