Designing Autonomous Robot Systems – evaluation of the R3-COP Decision Support System approach

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Abstract. Special features of autonomous robots – sensing and perception, decision making and reasoning, robust and safe behavior – lead to many common and well known concepts and technologies to be considered in the design. Requirements often common to an application domain should lead a system designer to appropriate available technologies for autonomy. We report experiences using a knowledge base (KB) decision support system to support the design work for selecting solutions (technologies) for autonomous robotic systems. We concretize the use of a KB and decision making tool with a well known user's problem, part identification, for which suitable sensor technology is to be found.

Keywords: Autonomous robots, Knowledge base, decision making.

1 Introduction

Service robots and lately even industrial robots tend to operate in a shared work space with humans and this sets challenges for robot system design. Special features of autonomy – sensing and perception, decision making and reasoning, robust and safe behavior – lead to many common and well known concepts and technologies to be considered both in the HW and SW design. With record high robot sales lately – in 2011 about 166 000 industrial robot units and about 2.5 million service robots have been sold [1] – more and more system designers are facing requirements common to an application domain. Huge numbers of available technologies and requirements leading to inherently complicated system structures make the design work really challenging and tools supporting the system, SW and HW design will be more than welcomed.

There have also been numerous efforts for developing technologies to support design automation. Among most popular has been automatic SW design, especially towards automatic composition of SW in the form of composing web service SW. For this there are principally four approaches [6]: 1) work flow representation, 2) model-based service composition, 3) automatic service composition based on mathematical representations like logics, calculi or algebras, and 4) AI planning techniques. Very relevant for autonomous robots have been Intelligent SW (multi-) agent technologies, which provide patterns and structures for organizing the autonomous robot SW system as subsystems and components for aspects like reasoning, planning, control and monitoring, see e.g., [4, 5]. These are typically similar or comparable to the model based composition category, though may include also AI planning characteristics.

In our approach we follow a model based approach, where already explored and well-established models are used to represent (SW) services and service composition. We use a knowledge base (KB) decision support system to facilitate the decision making when selecting solutions (technologies) for autonomous robotic systems. In [7] we have described the decision making procedure in more details and here give a shorter description for the decision support system, but give also an evaluation of our approach. The evaluation is carried out using common criteria given by Alavi [2] for assessment of Decision Support Systems (DSS). According to the evaluation results the decision making procedure applied here (PAPRIKA) [3] seems to be an appropriate way to retrieve solutions to design problems.

2 Knowledge based design of autonomous robot systems

Within our decision support system approach the user, e.g. a system designer, utilizes knowledge from a knowledge base (see Figure 1). An *expert* is a person with domain knowledge able 1) to formalize domain requirements and convert them into general requirement features, and 2) to describe technology in terms of their features. A *user* is typically a system integrator or a manager level person who may not have a deeper understanding of neither the available solution technologies nor the criteria required to address the user requirements, but does, however, have the knowledge to assess the relative importance between criteria. Based on the user requirements the decision support tool facilitates the coupling between expert and user knowledge by creating a model comprising criteria and categories, and by presenting potential solution technologies to the user. The expert verifies that the created model is valid and the user then performs a criteria ranking that establishes the ranking of the potential solutions.

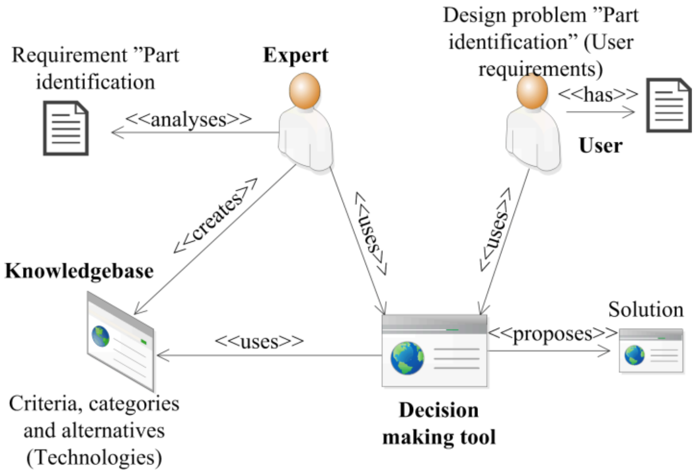

Fig. 1. Procedures for creation of a KB model and utilization of decision making tool

In the decision making procedure we use the *Potentially All Pairwise RanKings of all possible Alternatives* (PAPRIKA) [3] method for creating and retrieving solutions. PAPRIKA helps elucidate preferences of a set of alternatives by assigning weights to ordinal categories of evaluation criteria based on a trade-off process where the user has to indicate pairwise preferences between conflicting hypothetical alternatives (technologies). The category weights facilitate the calculation of an overall absolute score for any alternative rated on the criteria by simple addition; a higher overall score indicates a higher preference. PAPRIKA facilitates easy use of both qualitative and quantitative criteria due to its use of ordinal categories. For a qualitative criterion S*afety*, categories such as "high safety", "medium safety", and "low safety" could be used, and each alternative would then have to be evaluated by selecting the appropriate rating category. In our decision making procedure, solutions for a design problem are retrieved from the knowledge base model (comprising criteria, categories, and alternatives) which, as explained, are created from experts' knowledge. This is done through the following process:

1. Retrieve criteria, categories, and alternatives from KB based on requirements
2. Rate Alternatives on categories
3. Perform trade-offs
4. Calculate alternative scores
5. Rank alternatives.

In this paper a problem, "Part identification" – a common problem in many autonomous cooperative robotic systems – is considered and a preliminary knowledge base is utilized in the evaluation of the applicability of the decision making procedure. The online PAPRIKA decision making tool 1000minds (http://www.1000minds.com/) was applied in the decision making process.

The preliminary knowledge base was implemented as Microsoft Excel spread sheets where the requirements, criteria, categories and alternatives are presented for the selected requirements. Figure 2 illustrates relationships between requirements and their features as well as alternative technologies and their features as given in the KB and used by the Decision support system.

The set of requirements included the following: Part identification, Part localization, Part quality inspection and Part handling. The set of potential alternatives (or technologies) that were described in the knowledge base were:

- Part identification: Laser scanner + 2D camera, 2D camera, Radio Frequency Identification (RFID) tags, and Markings/codes
- Part localization: Laser scanner + 2D camera, 2D camera, and jigset pallets
- Part quality inspection: Machine vision, Manual
- Part handling: Automated, Semi-automatic

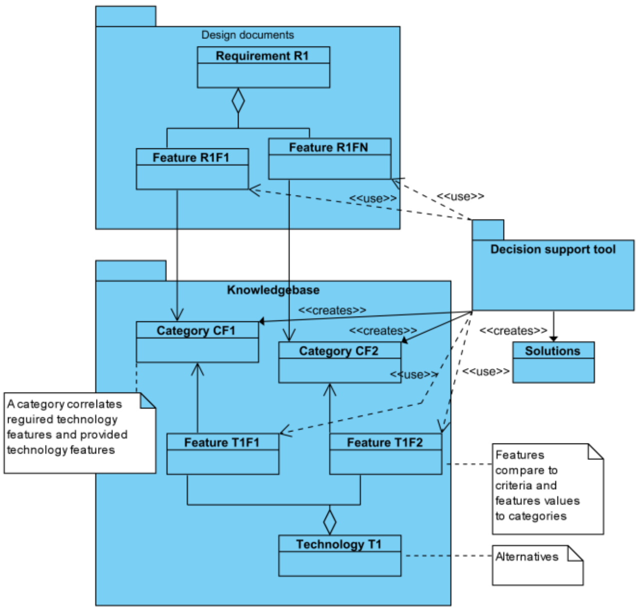

Fig. 2. Design support system architecture.

The decision making tool proposes a solution using a model of the user problem. Processing of solutions against the problem is based on a questionnaire, in which a user gives answers to the questions which are based on criteria, categories and alternatives. In the selection process the decision making tool creates a trade-off session for the user. After this has been completed, the tool suggests a solution to the user's problem based on the resulting category weights. The suggestion is a list of alternatives (solutions). The alternative with the highest score (%) is the most preferable solution.

3 Requirements, criteria, categories and alternatives

The overall structure of our preliminary knowledge base is illustrated in Figure 3. Solutions are organized around subsystems (Part Identificator, Part Localizer, Wooden Part Quality Inspector, Part Handler), for which actual implementations are given as integrated solutions, based on unit technologies, such as 2D and 3D cameras. The properties of subsystems (which the subsystems inherit/implement) act as an interface towards the requirements.

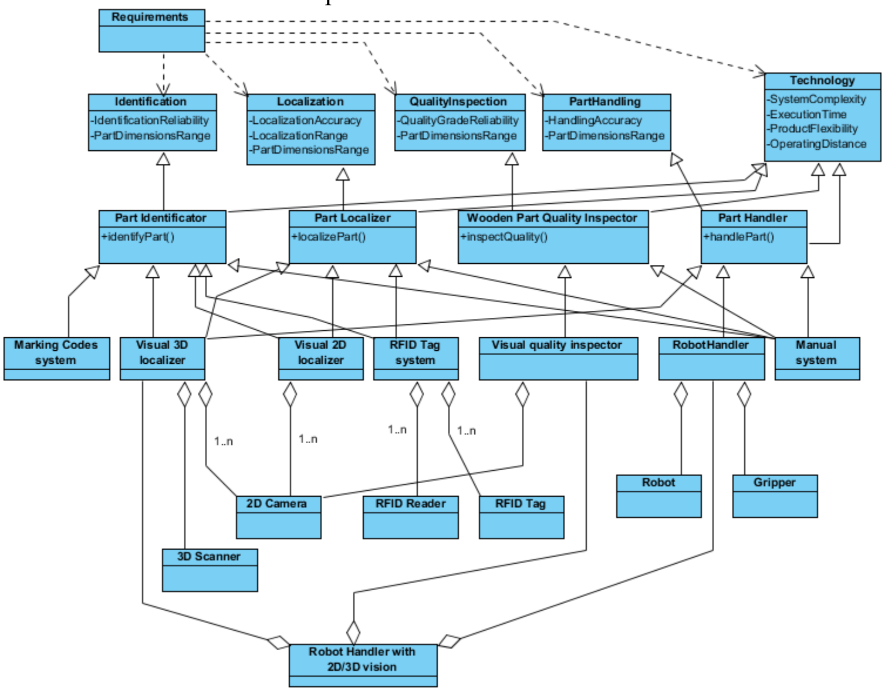

Fig. 3. Technology knowledge base with requirements dependencies.

For clarifying the processes of creating a model we will take a closer look at the requirement "Visual identification and localization of wooden parts". The actual alternative implementations were modeled for the Part Identification. Instance models were created with attribute values for the alternatives Visual 3D localizer, Visual 2D localizer, RFID Tag system and manual identification.

Table 1 shows criteria and categories concerning the "Part identification" design problem. Also the alternatives for the requirement are shown along with their category ratings. The alternatives are possible solutions (technologies). The columns under "Categories" show the categories for each criterion and the number of categories may differ between criteria. Under the "Alternatives" title the potential solutions for the requirement are shown. The criteria and alternatives were selected by experts' opinions. In this case the experts are the authors of this article.

Table 1. Criteria, categories and alternatives for the part identification design problem.

Criteria		Categories			Alternatives							
					Laser+2D camer		*2D camera*		*Rfld tag*		*Marking/codes*	
					Categ	*value*	*Catego*	*value*	*Catego*	*value*	*Catego*	*value*
System complexity: Num of sensors	high	mediur	low		low	3	low	1	high	10000	high	10000
Identification Reliability: successfully recognised	75%	80%	90%	95%	90%	90%	75%	75%	95%	97%	95%	97%
Execution time	>5s	3-5s	1-3 s	< 1s	>5s	5s	1-3 s	2s	>5s	5s	>5s	5s
Dimension accuracy	+-5 cm	+-3 cm	+-1 cm		+-1 cn	0.5cm	+-3 cm	2 cm	+-1 cm	0.5 cm	+-1 cm	0.5cm
Product flexibility: adaptability to new parts	low	mediur	high		high	high	mediur	medium	mediur	medium	mediur	medium
Contact free: operating range	0 m	0-0.1m	0.1-1 m	>1m	>1m	3m	>1m	3m	0 m	0m	0 m	0 m

The criteria, categories, alternatives, and alternative ratings from Table 1 were manually entered into the 1000minds online graphical user interface by the authors. Following this, the trade-off procedure was conducted in the system which consisted of a series of dilemmas that had to be answered by the user: "Which of these 2 (hypothetical) alternatives do you prefer (Left, Right or equal) given they're identical in all other respects." An example of such a dilemma can be seen in Figure 4.

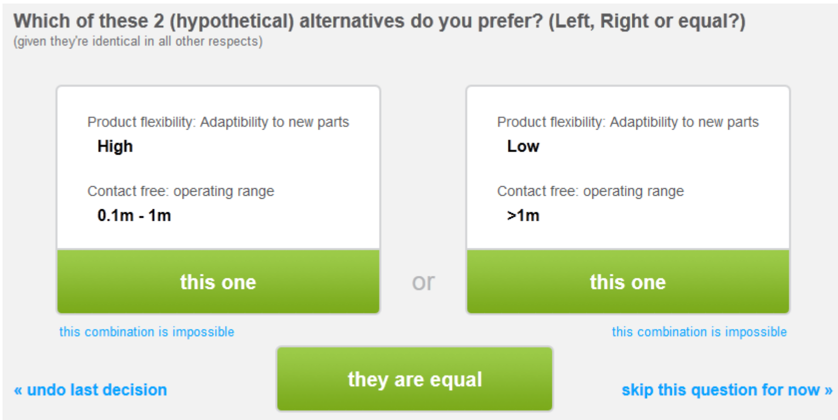

Fig. 4. An example of a trade-off question as presented by the 1000minds graphical user interface.

In this example two hypothetical alternatives (technologies) are selected with identical categories except on two criteria: "Product flexibility" and "Contact free". Here opposing categories are chosen by the system which constitutes a dilemma that the user has to resolve. Based on all the trade-off answers, the category weights are calculated leading to the final value model used for calculating the individual alternative scores. Table 2 shows the ranking proposed by the model and the ranking based on the expert opinion. Ranking proposed by the KB model and the experts are identical indicating a sound criteria model. As a solution, the laser range finder with a 2D camera will be selected.

Table 2. Ranking of alternatives.

Alternative	Score	Model rank	Expert rank
Laser+2D camera	94,7%	1st	1st
2D camera	80,0%	2nd	2nd
RFID tag	25,3%	3th	3th
Marking/codes	25,3%	4th	4th

4 Evaluation of the design methodology

We evaluated the design methodology, following the common criteria given by Alavi [2] for assessment of Decision Support Systems (DSS). In the following, two sets (Table 4 and 5) of criteria are given, and each criterion is evaluated based on the experiences in the assessment sessions. Alavi lists first potential – and general – benefits of decision support systems. Our design methodology experiment is evaluated against each expected benefit below, with justification/explanation based on the experiment.

Table 4. Benefits of decision support systems.

Benefit	**Contribution**
Provide information processing and retrieval capabilities	Yes/Yes
Evaluate the alternatives	Yes
Assist in identifying problems	No
Assist in interpreting the information	Yes
Provide fast (real time) analysis of current problem/opportunity	Yes
Suggest decision alternatives	Yes
Provide ability to ask "what if" questions	No
Manage executive time by scheduling daily activities	No
Increase decision confidence	Yes

The detailed evaluation results are as follows:

- Provide information processing and retrieval capabilities

  Information processing: YES

Information retrieval: YES

The decision making tool processes a solution for a user's problem based on the questionnaire. The expert opinions are not directly shown to the user.

- Evaluate the alternatives: YES

  The tool gives ranked alternatives as a list of solution candidates for the user's design problem. Ranking is based on score values, which are calculated from score values of each criterion. The solution with the highest score is the most preferable solution. By plotting the prices of the solutions vs score values the Pareto Frontier can be obtained. This presentation helps the user to choose a cost effective solution, if the price is an important factor for the user.

  This kind of presentation assumes that the user has some level knowledge of the problem's solutions (technologies). The user should at least be capable to evaluate that the solutions are practical for the user's problems. An extra user or expert may be needed for interpreting the results.

- Assist in identifying problems: NO

  The tool does not assist in identifying problems. It aims to find a solution for the user's problem.

- Assist in interpreting the information: YES

  The tool asks the user a series of trade-off questions and seeks a solution based on the answers.

- Provide fast (real time) analysis of current problem/opportunity: YES

  Analysis is fast if the user has input requirements specifications for his/her problem and is aware of the specifications needed by the tool.

- Suggest decision alternatives: YES

  The tool ranks solutions as a list. The decision of finally selecting right solutions is left to the user.

- Provide ability to ask "what if" questions: NO

  The tool gives three options for a question. User must select one of these.

- Increase decision confidence: YES

  From the use point of view the tool can be utilized in two ways. It can guide a non-experienced user in the right direction (assist in choosing right technologies) or it can confirm that the pre-selected technology is an appropriate solution (increases confidence). The tool supports decision making and it should not be used as the only tool in a design process.

Alavi lists also issues (or difficulties) in decision environments and perceived needs for decision support (Table 6). Our design methodology experiment is assessed against each issue, considering whether the design methodology contributes or does not contribute to the issue, with justification/explanation based on the experience in the experiment.

Table 5. Issues in decision environments and perceived needs.

Issue or difficulty	Contribution
Conflicting objectives or criteria	Contributes well
Having to decide without sufficient information	Contributes to some extent
High complexity in decisions	Contributes to some extent
Estimating the impact of decisions	Does not contribute
Not knowing the objectives in clear and measurable form	Contributes well
Deciding how much information is sufficient	Contributes well
Forgetting something that should have been included	Contributes to some extent
Communicating with the people involved in the decision	Contributes well
Being forced to decide under time pressure	Contributes well
Determining what information is relevant	Contributes to some extent

Issues and difficulties are more related to the model developing phase. These aspects are discussed in more details below from both user and expert points of view.

- Conflicting objectives or criteria: CONTRIBUTES WELL

  The decision process is based on the answers of a series of simple pairwise ranking questions. Conflicting objectives or criteria may lead to a non-preferable solution. Usually this can be avoided by conducting a new iteration with updated criteria, if the proposed solution does not meet the expert's opinions.

- Having to decide without sufficient information: CONTRIBUTES TO SOME EXTENT

  The decision making is not performed if insufficient information is provided by the user.

- High complexity in decisions: CONTRIBUTES TO SOME EXTENT

  High number of criteria can lead to a large number of pairwise rankings, resulting in high complexity decision making – or fatigue by the answering user.

- Estimating the impact of decisions: DOES NOT CONTRIBUTE

  Impact of decision is not estimated by the tool, this is left to the user.

- Not knowing the objectives in clear and measurable form & Deciding how much information is sufficient: CONTRIBUTES WELL

The tool supports the user by giving a questionnaire. The user should input requirement specifications for the problem before utilizing KB and should be aware of the needed specifications required by the KB analysis. In the development of the KB models (criteria, categories and alternatives) experts decide how much information is required. If solutions are not satisfying, the experts need to update criteria.

- Forgetting something that should have been included: CONTRIBUTES TO SOME EXTENT

  The KB models can be updated with a new iteration. If the number of criteria increases, this can lead to the complexity issue.

- Communicating with the people involved in the decision: CONTRIBUTES WELL

  The decision making process is based on the expert's and the user's opinion. Opinions of other experts or users can increase the reliability of the decision making procedure.

- Being forced to decide under time pressure: CONTRIBUTES WELL

  The development of the models may require several iterations. Lack of time may thus lead to the issue (being forced to decide…)

- Determining what information is relevant: CONTRIBUTES TO SOME EXTENT

  This is probably the most important issue when experts are developing criteria and answering to pairwise questions. This can be avoided by using several experts' opinions. The models should be created by defining as few criteria as possible in order to avoid complexity and irrelevant criteria. For instance, in the 1000minds tool the number of criteria is limited.

5 Conclusions

In this paper the applicability of the decision making procedure was described by using a "Part identification" problem – a common problem in many autonomous cooperative robotic systems – as an example. The procedure is based on the PAPRIKA approach and was also evaluated as a decision support system. On the basis of our experiences, the decision making procedure (PAPRIKA) seems to be an appropriate way to retrieve solutions to design problems such as "Part identification". The procedure enables development of rather simple tools from a user point of view. The user answers trade-off questions offered by the tool and the tool provides a list of ranked solutions based on a KB model which is derived from experts' knowledge. Also the cost of the solutions can be taken into account in the tool. The challenge of PAPRIKA approach is related to the retrieval of the models from experts' knowledge. Determination of relevant information can be difficult for the experts and if the number of criteria and categories are high, the complexity of the retrieval process may lead to non-preferable solutions. Further on, values ranges for the categories could be easily matched to the specifications of the technical alternatives. Several iterations may be required in creating the knowledge based models so the development of a useful model can be time-consuming.

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