Technical Design Approach for Autonomous Outdoor Transport Systems based on an Extension of Axiomatic Design using Metrics

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Abstract. This contribution focuses on the technical design of autonomous outdoor transport systems operating on factory premises. Outdoor applications present a high degree of complexity, which is reflected in the technical design of these vehicles. The requirements they must fulfill are higher than for indoor applications. Hence, the results of the technical design are crucial to enable the correct use of such systems. Axiomatic Design hereby offers a methodological basis for the systematic derivation of solution parameters for the technical design of autonomous outdoor transport systems. Functional metrics are introduced in addition to the conventional Axiomatic Design method to support the formulation of functional requirements and to reduce the subjectivity in the design process. The technical design approach that was developed is applied in the form of a framework.

1. Introduction

The term automated guided vehicle (AGV) is widely used in both literature and practice [1]. Conventional AGVs perform logistics tasks, such as transporting and handling materials that are assigned to them in an automated manner. They do so by following a pre-defined route within a defined action area [2]. Extensions of these vehicles are often described in literature as autonomous mobile robots (AMRs), autonomous intelligent vehicles (AIVs) or autonomous transport systems [3]. They represent a smarter and more intelligent version of an AGV [4]. This means that they have a decentralized planning, execution and control and help optimize internal material and information flows by cooperating and interacting with other systems and with humans [5]. However, since they not only drive indoors but also outdoors on factory premises, and since they also act autonomously, they have to satisfy significantly higher requirements, which are reflected in the complexity of their technical design.

Adaptable, comprehensive and intelligent transport solutions are required to meet the increasing demands on the flexibility of material supply chains within logistics [6]. Autonomous outdoor transport systems are one possible answer to this. However, the technical design of these systems is highly complex [7]. Even if single requirements are known, it is still not clear how these should be organized and which technological solutions are the best for certain requirements. Axiomatic Design (AD) provides a systematic research method to tackle this issue, generating a structured technical design.
approach for autonomous outdoor transport systems. Based on the collection of customer needs (CNs) and the derivation of functional requirements (FRs), the research team also introduces and adopts functional metrics (FMs) to complement FRs. Thus, it is more likely that the chosen design solutions will successfully satisfy the CNs [8]. Furthermore, FMs allow the most suitable design parameters (DP) to be selected for a certain FR. According to the decomposition process (zig-zagging and mapping), FMs are assigned at each hierarchy level to the respective FRs, for which DPs are then generated. The aim of this paper is thus to present a technical design approach for autonomous outdoor transport systems in the form of a framework based on an extension of AD with the aid of metrics.

2. Methodology

In addition to the traditional use of AD according to Suh [9], FMs were also implemented in this research work. Several authors have already dealt with the use of metrics within AD. These include Brown and Henley, Cochran et al. and Melnyk et al., who refer to metrics as an important link between strategy, execution and eventual value creation [8, 10-13]. FMs are used for quality assurance and suitability verification of the individual FRs and the respective DPs. Metrics ensure that if multiple DPs are selected, the most appropriate DP for a given FR will be chosen. Moreover, they support the formulation of the FRs and consolidate their informative value by also strengthening the independence axiom [8]. Thus, we are able to reduce subjectivity in the design process and provide a basis for comparison.

The methodology for determining FMs in this paper is based on the approach developed by Henley and Brown [11]. The authors derive an FM for each FR-DP pair at each hierarchy level of the decomposition. However, before we can proceed with the gathering of CNs as well as mapping and decomposition of DPs and FRs, we first present the methodology needed to derive the technical design framework of autonomous outdoor transport systems using metrics (figure 1).

As implied by the AD approach, the two axioms (independence and information) serve to verify FRs and avoid coupled designs [14]. To reinforce the independence axiom, we additionally attribute an FM to each FR on each hierarchical level. On this basis, the research team implements the following five steps: determination of CNs (i), transformation of CNs into FRs at the top-level (ii), application of FMs at the top-level (iii), mapping of the DPs to the top-level FRs (iv) and finally decomposition (zig-zagging) and mapping of lower FRs using FMs according to the top-down principle (v).

2.1. Determination of CNs
The CNs used in this study are adapted from the previous work of Clauer et al. [15]. A systematic literature review and semi-structured interviews about the implementation of outdoor AMRs were used to identify these CNs. However, since this paper focuses primarily on the technical design of
autonomous outdoor transport systems, and not on the overall implementation process, the following attribute is selected: provide solutions for autonomous material handling on factory premises.

2.2. Transformation of CNs into FRs at the top-level
Based on the representative CN designated in the previous subsection, it is possible to define the FRs at the top-level that represent the key requirements. Considering the objective of this work, the top-level key requirement (FR₀) for the technical design of an autonomous outdoor transport system is defined as: “Handle and transport material autonomously on the factory premises”. To satisfy this requirement, FR₀ is assigned a solution (DP₀) in the physical design domain: “Technical design framework for autonomous outdoor transport systems on the factory premises”. The proposed DP₀ is formulated in a very general and abstract way. Therefore, it has to be decomposed into further FRs to prompt concrete parameters and solutions for the design framework:

| FR  | Description                                      |
|-----|--------------------------------------------------|
| FR₁ | Certify sturdy hardware components for outdoor use |
| FR₂ | Ensure robust and sustainable navigation software for the outdoor environment |
| FR₃ | Interact independently in a dynamic environment   |

2.3. Application of FMs at the top-level
According to the approach shown in Figure 1, we first assign FMs to the top-level FRs before formulating their respective DPs. The assigned FMs aim at identifying the most appropriate DP for a given FR. The correctness and meaningfulness of the metrics are indispensable in order to achieve this [13]. For this purpose, the following FMs are assigned to the top-level FRs:

| FM  | Description                                      |
|-----|--------------------------------------------------|
| FM₁ | Mean time between failures (MTBF)                |
| FM₂ | Availability in the operative environment        |
| FM₃ | Availability in a highly complex environment      |

To ensure that the individual hardware components of the vehicle are robust enough for outdoor use and are thus able to withstand different weather conditions (snow, ice, rain or fog) as well as road conditions (bumps, curbs or ruts), the MTBF is identified as an appropriate metric. The higher the MTBF, the more reliable and robust the components will be. The second FR focuses on the software part of the transport systems. The higher the availability in the operating environment, the more robust and sustainable the navigation software. In addition to hardware and software requirements, independent interaction in a dynamic environment characterizes the autonomy of the vehicle and thus represents an elementary pillar of the technical design framework. The availability in a highly complex environment beyond the standard operational setting is a suitable metric for FR₃ to measure this requirement.

2.4. Mapping DPs to the top-level FRs
According to Suh, a central feature of AD during the mapping and decomposition process of DPs is a solution-neutral formulation of FRs. The goal is to think creatively and freely about possible solutions without being influenced by existing or seemingly obvious solutions, thus restricting the design space [16]. Top priority is always given to compliance with the independence axiom and the information axiom as well as the consideration of the collectively exhaustive and mutually exclusive approach (CEME) according to Thompson [17]. Starting from the top-level key requirement FR₀ and its design solution DP₀, as well as the previously derived top-level FRs including their FMs, we are now able to derive DPs at the first hierarchy level. Figure 2 illustrates the FR-DP tree at the top-level.
Figure 2. Graphical representation of the FR-DP tree at top-level using Acclaro DFSS.

To verify whether the independence axiom is fulfilled, the top-level FRs and DPs are expressed in a matricial form inside a design matrix (DM) [18]. This DM, presented in Equation 1, is characterized by a decoupled design in the form of a triangular matrix.

\[
\begin{bmatrix}
FR_1 \\
FR_2 \\
FR_3
\end{bmatrix} =
\begin{bmatrix}
X & 0 & 0 \\
0 & X & 0 \\
0 & 0 & X
\end{bmatrix}
\begin{bmatrix}
DP_1 \\
DP_2 \\
DP_3
\end{bmatrix}
\] (1)

The resulting decoupled triangular matrix shown in equation 1 illustrates the connection between DPs and FRs. The technical suitability testing of hardware components (DP1) fulfills FR1 and can be functionally verified using the MTBF (FM1). DP1 has no relation to any other subsequent FR, since it refers exclusively to the frame, chassis and housing of the transport system. High-quality environmental maps with a robust and accurate localization (DP2) have an impact on the independent interaction in a dynamic environment (FR3). The more accurate the environmental maps, the more independently a transport system can operate within a dynamic environment. Moreover, a closer look shows that the dependencies existing between the FRs and DPs create manageable feedback loops if the DPs are implemented in the correct order from left to right [19-20].

2.5. Decomposition and mapping of lower FRs using DPs

The proposed solutions (DP1-3) are still too abstract for a concrete design framework. Therefore, they are decomposed into further sub-requirements. Starting from DP1, the following lower level FR-DP-FM trios for determining technical suitability testing (DP1) are derived (table 1).

| FR          | DP                               | FM       |
|-------------|----------------------------------|----------|
| FR11        | Protect against the intrusion of | DP11     |
|             | particles and water              | Protection rating and protection class | FM11   |
| FR12        | Test mechanical stability and    | DP12     |
|             | durability                        | Virtual mock-up tests of designed components | FM12   |
| FR13        | Employ reliable mechatronic      | DP13     |
|             | components                       | Endurance tests | FM13   |

High-quality environmental maps with a robust and accurate localization (DP2) are also decomposed into lower FRs. Table 2 shows the FR-DP-FM trios for DP2.
Table 2. Decomposition of DP_2 – high-quality environmental maps.

| FR  | DP             | FM                        |
|-----|----------------|---------------------------|
| FR_{21} | Send/receive information about the current location | DP_{21} Localization technologies | FM_{21} Precision and accuracy of the data |
| FR_{22} | Determine own position on a map at any time | DP_{22} Detailed and synchronized map | FM_{22} Deviation compared to real position (+/- 1 m) |
| FR_{23} | Reduce sensor noise | DP_{23} Suitable software and hardware solutions | FM_{23} Signal-to-Noise-Ratio (SNR) |

Localization technologies, especially for outdoor environments, have a great impact on the robust and accurate localization of an autonomous transport system. DP_{21} therefore needs to be further decomposed to a third hierarchical level so as to obtain accurate and concrete DPs (table 3).

Table 3. Decomposition of DP_{21} – localization technologies.

| FR  | DP                         | FM                        |
|-----|---------------------------|---------------------------|
| FR_{211} | Determine the position in a fixed reference system | DP_{211} GNSS | FM_{211} Deviation from the real value (+/- 1 m) |
| FR_{212} | Determine the distance covered | DP_{212} IMU and odometry | FM_{212} Precision and accuracy of the calibration |
| FR_{213} | Determine the position relative to a known position | DP_{213} Combination of visual sensors with environmental objects | FM_{213} Robust recognition |

Detailed and synchronized maps (DP_{22}) include further sub-requirements, which are shown in table 4.

Table 4. Decomposition of DP_{22} – detailed and synchronized map.

| FR  | DP                        | FM                        |
|-----|---------------------------|---------------------------|
| FR_{221} | Calibrate robot position | DP_{221} Definition of reset positions (start/finish/wait position) | FM_{221} Accuracy from known positions |
| FR_{222} | Update map continuously   | DP_{222} SLAM algorithms  | FM_{222} Update frequency |
| FR_{223} | Define possible driving areas | DP_{223} Definition of driving and restricted areas on the map | FM_{223} Clarity of boundaries |

DP_{2} has now been broken down to a level of detail suitable for the technical design framework. The last decomposition within the technical design field of an autonomous outdoor transport system concerns the environmental perception and understanding, which represents the final pillar of the framework. It is further decomposed into three sub-requirements to once again obtain feasible physical solutions.

Table 5. Decomposition of DP_{3} – environmental perception and understanding.

| FR  | DP                        | FM                        |
|-----|---------------------------|---------------------------|
| FR_{31} | Obtain sufficient information from sensors | DP_{31} Data from cameras and laser scanners (2D/3D) | FM_{31} Density of the point clouds |
| FR_{32} | Process sensor data       | DP_{32} Sensor fusion     | FM_{32} Quality of results |
3. Technical design framework

The proposed technical design framework for autonomous outdoor transport systems results from the extracted DPs, which in turn can be traced back to the corresponding FRs and FMs. The framework is based on three main pillars: first, technical suitability testing of hardware components for outdoor use; second, high-quality environmental maps; and third, environmental perception and understanding through sensor technology with corresponding response scenarios. Each pillar includes different solutions that must be considered in the technical design of an autonomous outdoor transport system. It should be noted that the order of the pillars also plays an important role during the implementation process. Due to the connection between DP3 and FR3, failure to follow the predefined order can lead to confusing circular reasoning, characterized by the violation of the independence axiom.

![Technical design framework for autonomous outdoor transport systems](image)

**Figure 3.** Proposed technical design framework for autonomous outdoor transport systems.

4. Conclusion

In connection with the numerous challenges and difficulties faced by autonomous transport systems in an outdoor environment, demands on the technical design of these vehicles have grown substantially. To counter this increasing degree of complexity, in particular during the design phase, the present work presents an extension of the AD method with the use of FMs. Through their implementation in the approach, FMs support the mapping process of DPs and reinforce the importance of FRs. This ensures an optimal choice of DPs with regard to CNs. This systematic approach enables the identification and classification of three main technological requirements that characterize the technical design of autonomous outdoor transport systems. On the basis of these findings, the research team built and presented a framework based on three pillars for the technical design of autonomous outdoor transport systems, laying the foundation for further work in this field.

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