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Technical Concepts for Inspecting UAVs for Damage

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Abstract

The current movement toward urban air mobility (UAM) [1] shows the importance of a ground-based infrastructure network to provide urban air vehicles (UAV). To ensure the safety aspect it is necessary to develop a system that can inspect the arrived UAV for damages. Therefore, technical concepts for inspecting UAVs for damage are elaborated. To identify the best system for technical development under the presented concepts evaluation criteria must be defined and applied. These include properties, technical systems, and other criteria such as the costs. In the first step for every UAV inspection system, the differences between the motion sequences will be examined. In the second step, there will be an investigation of the sensor systems presented. In conclusion, the systems with the best results in both parts are merged for an inspection setup for further investigations.

Keywords: MRO, ground-based infrastructure, skyport, unmanned aerial vehicles

1. Introduction

The increasing traffic volume in urban areas in combination with the wish for individuality is a driving factor for the movement to UAM [1, 2]. However, there is a target conflict with the ground-based infrastructure as the systems are in development and not fully realized yet, like the UAVs, and have a huge demand for space and this doesn't exist in urban areas. Furthermore, the UAM will mostly take place above a security-sensitive place: the urban region. Hence, it is necessary to develop a system that ensures safe and reliable UAM. A condition analysis can determine unscheduled events, which leads to additional aircraft utilization [3]. The establishment process is characterized by development pressure, missing maintenance guidelines, certification processes and the need for time and cost-efficient systems. Currently, the maintenance, repair, and overhaul (MRO) processes are done manually which entails high costs for employees and high requirements for their training, high time demand, and not reproducible results [4]. To solve these problems reliable automation must be designed.

This paper is structured as follows. Chapter 2 describes the methods, criteria, and boundary conditions that are used for the elaboration of the technical concepts for the inspection of the UAVs. Here the UAV and their possible damages and classification, the used methods, and evaluation criteria are presented. In chapter 3 the motion concepts for the inspection of UAVs are showcased and the evaluation criteria will be applied. The same will be conducted for the techniques for damage detection in chapter 4. The results will be discussed in chapter 5 and chapter 6 will give a summary of the work done so far and an outlook.

2. Methods, criteria and boundary conditions

2.1 The vehicle under investigation

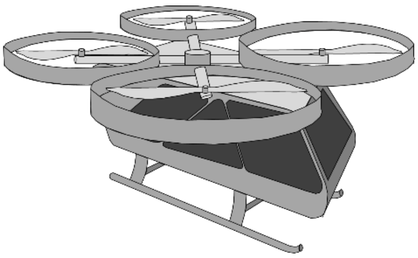

Figure 2.1: Schematic eVTOL for the MRO concepts use case

For the investigation, a standardized vehicle is needed. Therefore we analyzed the vehicles with the highest probability of a successful market entry [5]. For this purpose, we designed the schematic eVTOL in figure 2.1. It is necessary that the technical system for inspecting the UAVs for damage can act modular. The market will derive many difficult designs of UAVs [5] so there is a need for a universal system. For a modular inspection of the UAV, we need to divide the vehicles into sections that appear often [6, 7, 8, 9, 10, 11, 12, 13, 14, 15, 16]. We chose the following sections that are shown in table 2.1.

Table 2.1: Divided sections of the UAVs that appear often in the currently published designs of the manufacturers and their categorization in possible flight checks

Category	System	Pre-Flight-Check possible?		Check only in lifecycle maintenance possible
		External	Internal	
Drivetrain	Rotor/ Tiltwing/ Tiltrotor	✓	✓	
	Batteries		✓	
	Cables		✓	
	Gearbox			✓
	Electric Engine			✓
Structural Elements	Rotor Enclosure	✓	✓	
	Cabin Enclosure	✓	✓	
	Skids/ Landing plant	✓	✓	
	Rotor-Cabin-Compound	✓	✓	
	Hull	✓	✓	
	Cabin and interior			✓
Avionics	Flightcontrol and –management		✓	
	Communication		✓	
	Navigation		✓	
	Sensors		✓	
	Datalinks		✓	
Electric Systems	Lights	✓	✓	
	Air conditioning			✓

Here we take note, that only the exterior systems can be inspected by an automated system in the first step for a quick pre-flight check, a check of interior systems wouldn't raise the system's safety by a high amount and would take too much time and therefore the system itself will not be profitable. For the electric systems, e.g. avionics, a self-check with data links is possible or preparation steps need to be done, like removing the shuttering. Hence, the interior systems full check will be conducted e.g. an extensive 100 h check. The time duration between the systems security checks will be dependent on the life cycles of the vehicle's materials in the cause of their load situations, such that a reliable flight can be guaranteed. In this paper concepts only for the pre-flight check will be shown. Concepts for an extensive security check of the vehicles need extra investigation and have other boundaries than the pre-flight check – e.g. a longer timeslot or a wider variety of MRO options at a better-equipped vertiport workspace in case of a centralized MRO vertiport - and will be considered in another publication. It needs to be considered that all the pre-flight check steps will be conducted in full maintenance again. Table 2.1 shows only the earliest point where inspection of a specific system is possible. For reliable damage detection, it is necessary to build up a knowledge base of possible damages to the vehicles. The classification of these damages is conducted in chapter 4.

2.2 Used methods and evaluation criteria

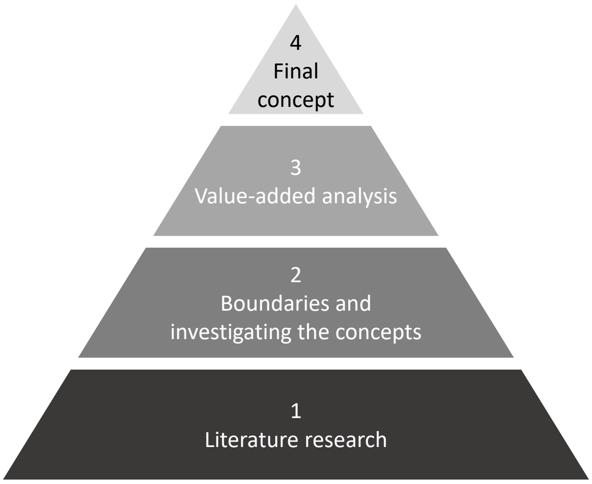

Figure 2.2: The used methods for the development of the technical concepts and their sequence

First, literature research was conducted to collect all the information that is needed to develop the technical concepts that will be examined in a value-added analysis in the following chapter. For this part, the compositions of the vehicles with the most probably market entry were checked [5]. Then we picked out their possible and often damages [17, 18], lifecycles [19], and types of sensors which will be shown detailed in chapter 4 to detect these damages in a quick and reliable pre-flight check. After the literature research, we set the boundaries for the development of the concepts and started the investigation of five concepts which will be presented in the next chapter. In this step, we specified the evaluation criteria for the value-added analysis of the concepts. Therefore we contrast the here chosen motion sequences of the pre-flight check as a first step. In a second step, we compare the found sensor types. The selection of technologies is based on the literature research for the most promising methods in the current trends in the market for equivalent transport systems, e.g. aircraft or helicopters. Then we applied the evaluation criteria to the motion and measurement methods separately and conducted a value-added analysis. With the results of this analysis, we merged the best-ranked technologies to find a holistic concept for the pre-flight check of the standardized vehicle. After this, we determined the problems that still exist, so that the final concept can be further investigated. The used methods for the development of the technical concepts and their sequence are shown in figure 2.2.

The evaluation criteria derive from the main requirements of the pre-flight check and are shown in table 2.2. The evaluation criteria will be different for both sections of the value-added analysis to evaluate the concepts from different points of view. The first section (I) will refer to the analysis of the motion sequences, and the second section (II) will relate to the analysis of the various sensor types and their suitability for a quick and reliable pre-flight check. Before developing the shown concepts we conducted small literature research on the current pre-flight check trends as well [20, 21, 22, 23].

Table 2.2: Evaluation criteria for the value-added analysis of the concepts in two steps. First, the analysis of the motion sequences (I), and second the analysis of the sensor types (II) of the pre-flight check of the vehicles.

Section	*Main sections*	*Detailed criteria*	*Goodness*
I, II	*properties*	*Speed*	+++, ++, +, *o*, -, --, ---
I		*Reachability of narrow spaces*	
I		*Size*	
I, II		*Impact of vibrations*	
I,II		*Accuracy*	
II		*Quality of the sensor data*	
I		*Scalability*	
II		*Reliability*	
I, II	*technical systems*	*Technical feasibility*	
I, II		*Flexibility/ Unisex system*	
I, II	*other*	*Costs*	
I, II		*Lifespan*	
I, II		*Need of own MRO*	*Yes/ no*
I, II		*Amount of own MRO*	+++, ++, +, *o*, -, --, ---

3. Movement concepts for the inspection of UAV

3.1 The motion concepts

The drone

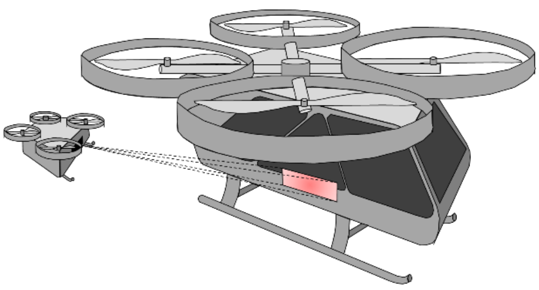

Figure 3.1: Inspection with another smaller drone

The first concept stands out with its high flexibility and is shown in figure 3.1. The drone is a small drone with as to four rotors. The sensors will be applied on a gimbal either under or on a side of the drone to allow maximum stability and reachability for the sensor data to be captured. The high flexibility is the best advantage of this concept. The drone can inspect the vehicles' difficult surfaces, e.g. the rotors, as well as the narrow areas, e.g. the skids.
Additionally, the distance of the drone to the vehicle is highly variable which allows various types of measurement methods. The drone can even take over other inspection tasks on the vertiport if it's not needed for the vehicle inspection at the moment. Due to the way this concept moves, a very unstable measurement is the consequence. A gimbal can reduce the uncertainties to a minimum but it will be burdened by measurement uncertainties nevertheless. Further, the drone needs an energy supply that determines the operation times. The weight of the drone and its dimensions are key factors for its operation duration which implies that not every sensor can be installed. The data link needs additionally a wireless system.

The kinematic

The kinematic is a much less flexible system than the drone and is shown in figure 3.2. It consists of a multiaxial kinematic to which the needed sensors are mounted. This concept can either move on rails or the vehicle could be moved on a turn-around system. The vehicle turn-around system can lead to reduced vibrations at the kinematic and high-quality measurement. But this needs an additional investigation for the turn-around of the vehicle. Because it needs to be universal for the different vehicle types high costs are possible. The generally stable and precise movement of the axes of the kinematic is one of the advantages. This results in a high-quality measurement.

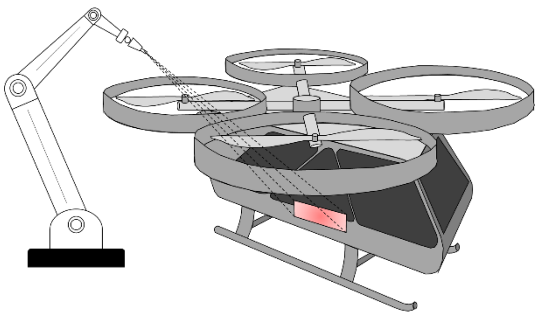

Figure 3.2: Inspection with a kinematic system

Also, this concept has a higher payload and wider dimensions so that more sensor types are possible. A gimbal e.g. is not needed because the kinematic is not in a movement sequence while taking the measurement data like the drone is. On the other side, the inspection process is slow because of the possible accuracy. To reach every spot of the vehicle many axes and high reachability are needed which ends up in higher costs. Furthermore, the system can't leave its operation area, so efficient usage of the time slots where the kinematic is not needed is not feasible. Data links and energy supply can be solved with a connection by wire.

The cable robotic

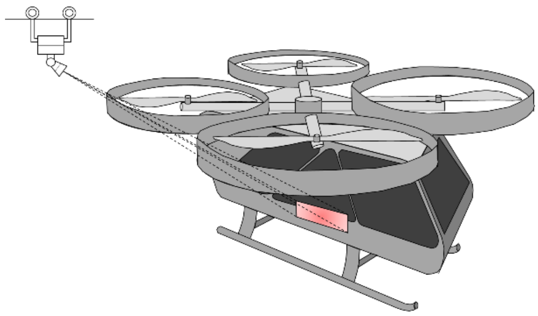

Figure 3.3: Inspection with cable robotics

For the next concept, outer construction is necessary. It consists of a cable on which the cable robotic can move and is shown in figure 3.3. Additionally, a construction for a turn-around of the vehicle is needed in the same way we contemplated it for the kinematic. The cable robotic can only inspect the top construction parts of the vehicles which are the rotors and their enclosures. In its movement way, this concept is very fast and flexible, provides high-quality measurement data, and is not restricted on construction dimensions or weight.
But for this, additional construction is necessary which reduces the flexibility of the investigated concept. The cable robotic may need an e.g. gimbal. The measurement will be conducted if the system stands still, but the cable can swing as a result of the cable robot's moves. Energy supply and data links can be solved through the cable on which the robot is moving.

The mobile kinematic

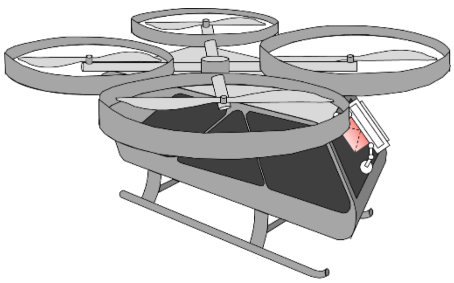

Figure 3.4: Inspection with mobile kinematics

This concept is a mobile robot that is moving autonomously on the surface of the vehicle and is shown in figure 3.4. The needed sensors will be mounted in the center of the system. The mobile kinematic provides very high-quality measurement data because its distance to the surface to be inspected is very low and the speed of the movement of the kinematic itself is very slow, but on the other side this ends up in a laggard measurement. Otherwise, the small distance doesn't allow a general overview of the status of the vehicle like the drone does.
Still, the mobile kinematic can only move on the surface of the hull of the vehicle, not on e.g. the rotor or the skids, because their surface is too complex. Thus, an inspection of these sections is not possible with this concept. The energy supply and the data link can be realized with an external wire. Because of its stable and precise movement, the mobile kinematic doesn't need any support structures, e.g. a gimbal or a turn-around system for the vehicle, so the costs for these structures omit.

The handheld system

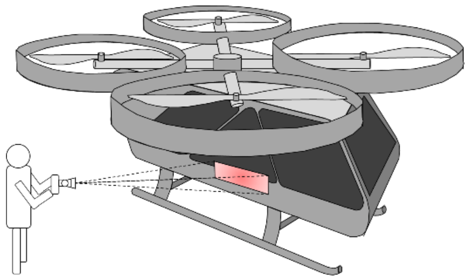

Figure 3.5: Inspection with a handheld system

The handheld system is a small inspection method that an employee can use for inspecting the drone. It is shown in figure 3.5. For the handheld system only a few sensor systems, e.g. LIDAR, are eligible because the dimensions, weight and sensitivity to vibration and unstable movements of the sensors are the driving requirement. The movement of the handheld system has the highest flexibility and the lowest costs of the five concepts. The operation with an employee requires additional safety requirements, because of the possibility of an accident, and training which makes the concept more complicated.
The handheld system needs wireless data links and a portable energy supply.

3.2 Value-added analysis of the movement concepts

To choose the concept with the best overall performance for a pre-flight check of the vehicles a value-added analysis of the movement concepts is necessary. Hence, we set up table 3.1 in which the set detailed criteria table 2.2 above were used. The criteria aren't weighted, because we deem every criteria's impact as equal. As it can be seen from the value-added analysis, the drone is suitable for quick inspection where high flexibility and comparative low amount of motion precision are needed. The drone has relatively low costs and a high lifespan with a fairly low amount of its own MRO. The kinematic is a slow but high-quality and accurate motion option but needs a high amount of its own MRO. Its life span is very high. The cable robotic is the fastest concept because of its precise motion sequences on the cable. Though it is not flexible for all inspection areas and the costs are high, because of the needed external construction. The mobile kinematic is the slowest, but the most accurate movement system, of all valued systems. Because of its proximity to the surfaces which are to be inspected the motion will be very exact.

Table 3.1: Assessment of the movement concepts with a value-added analysis

Main sections	*Detailed criteria*	*Drone*	*Kinematic*	*Cable robotic*	*Mobile kinematic*	*Handheld system*
properties	*Speed*	++	--	+++	---	-
	Reachability of narrow spaces	+	+	-	---	++
	Size	++	---	---	o	+++
	Impact of vibrations	--	++	++	+++	---
	Accuracy	-	++	+	++	---
	Scalability	+++	o	--	+++	+++
	Technical feasibility	+++	+++	+	+	o
	Flexibility/ Unisex system	+++	+	-	+	++
other	*Costs*	-	---	---	-	++
	Lifespan	+	++	+	o	o
	Need of own MRO	*Yes*	*Yes*	*Yes*	*Yes*	*No*
	Amount of own MRO	+	--	---	---	++

But the mobile kinematic needs high attention, because it needs to be put on the vehicle's surface by an external force, e.g. an employee, and even be removed after the inspection task is done. The handheld system is very flexible, has low costs and is easy to implement into the vehicle. But through its circumstance that it needs an employee for its handling only a partly automated system can be reached with this concept. The employee needs to be trained for the operation with this concept and needs more strict security requirements.

4. Techniques for damage detection for UAV

For the selection of possible sensor types and their assessment in a value-added analysis, it is necessary to build up a knowledge base about operational scenarios. Possible is one sensor or a combination of a few sensors. These sensors should inspect the vehicle's surfaces visually and the first layers of its volumetric parts, because damages could hide behind the surface. The materials of the vehicles vary from matrix-fiber components to metal, glass or plastics. The causes of injury are foreign bodies, collision, weather, lifecycle exceedance, construction problems, or human failure. The impacts are structural, propulsion system, and power supply or avionics failure. We decided to analyze thermography (1), shearography (2), visual inspection with a camera (3), white light interferometry (4), LIDAR (5) for the surface inspection part and x-ray computed tomography (6), ultrasonic method (7), eddy current method (8) and microwaves (9) for the volumetric inspection of the vehicle. The thermography conducts its detection through differences in the vehicle's thermal conductivity and heat capacity. It is suitable for large components, can be used mobile, and has short measurement periods. But the thermography has low penetration, uses sensitive and expensive sensors, and loads the vehicle thermally [24]. The shearography is a coherent optical measurement method based on the laser speckle technique. It has short measurement time needs, can be used mobile, and is suitable for the inspection of large components. The shearography has otherwise a low penetration and is only useful for simple geometries and overlapping of damages could lead to a wrong measurement result [25, 26]. Otherwise, the visual inspection could be realized with a camera so surface injuries could be detected. This is a mobile concept that can give depth information with triangulation, is cheap, and can inspect large parts very quickly. However, it has disruptive effects, a limited detection through the camera's resolution and its deviation and distortion [27]. White light interferometry uses the interference of broadband light. It convinces with its high resolution and its possibility for high penetration but is very sensitive, expensive, and needs a high amount of reflection [28]. LIDAR sensors emit laser pulses and detect the light backscattered. They are easy to handle and allow a big measurement area. Though they detect absorption or strong reflection with certain orientations of the surfaces [29]. For the volumetric inspection of the vehicle, x-ray computed tomography is suitable. It provides good results for the detection of delamination, porosity, ondulation, and fiber breakage within the fiber-compound materials of the vehicle. With this method the visualization of structural boundaries is possible and it has a very high resolution. Further, it is very expensive, slow, and lavish and needs radiation protection [30]. The ultrasonic method provides good results for the delamination and the porosity, not for fiber breakage. It has high penetration and resolution and is mobile and quick. But often a coupling media is necessary and it is only suitable for low component complexities and high surface qualities [31, 32]. The eddy current method is an electromagnetic method for the inspection of volumetric components. It is quick, mobile, cheap, and has high resolution. Otherwise, it is only suitable for electrically conductive materials and gives only less depth information [33]. The microwaves method is quick, mobile, and cheap. But it is like the eddy current method only suitable for electrically conductive materials and has a low resolution and fewer depth information [34]. In table 4.1 the value-added analysis of the chosen sensor types is shown.

Table 4.1: Assessment of the sensor types with a value-added analysis

Main sections	*Detailed criteria*	*1*	*2*	*3*	*4*	*5*	*6*	*7*	*8*	*9*
properties	*Speed*	+	+	+++	-	-	---	+	+	+
	Impact of vibrations	+	-	--	---	+	+	+	++	+
	Accuracy	+	+	-	+++	+	++	++	++	*o*
	Reliability	+	+	*o*	+	+	+	+	*o*	+
	Flexibility	+	+	+++	*o*	+++	-	--	---	---
other	*Costs*	--	-	++	---	+	---	--	--	--
	Lifespan	++	++	*o*	+	*o*	++	+	+	++

As it can be seen from the value-based analysis we conducted for the sensor types, the thermography has an overall good rating, but it's to note that the thermal load for the vehicle is not acceptable since it reduces the lifespan of the vehicle hull. The shearography is, therefore, more suitable than the thermography but has some disadvantages in the sensitivity to vibrations and costs. The camera seems to be the best solution for quick but not high-quality measurement. The white light interferometry stands in contrast to the camera solution with its slow measurement process but high-quality inspection data and it has the highest penetration of all viewed surface inspection methods. But for the high-quality data, a still-standing pose is needed, otherwise, the vibrations of the motion sequence will reduce the quality of the inspection. The LIDAR system has average values. The x-ray tomography provides high-quality data and has high penetration, but the disadvantage of needed protection of the x-rays leads to an additional construction to cover the vehicle while inspecting which leads to high costs and high system complexity. The ultrasonic method is the only method of the four proven volumetric inspection methods which is technically feasible without any extra materials or constructions if used with air. It is a slow, but very high-quality measurement method which provides a high penetration. Both the eddy current method as well as the microwaves need electric conductive materials and because the vehicle doesn’t consist most of electric conductive materials these two methods are not useful for the inspection of the vehicle.

5. Results and discussion

From the value-added analysis of the motion concepts we conducted in chapter 3 we found that the drone, the kinematic, and the handheld system could be useful for the pre-flight check. The cable robotics external construction is too complex and inflexible for the here shown use cases. The mobile kinematic can’t provide a fully automatic operation scenario, so we don’t consider it anymore. The value-added analysis done in chapter 4 shows us that for quick surface detection the camera is the most suitable option. It will be reasonable to use it for a quick pre-flight check of the vehicle. The camera could be used with the drone and two ring lights for the bright- and darkfield illumination. In a second step, the white light interferometry or the air ultrasonic method can be used to scan regions, where the camera detected a failure, again and specify the failure, because it can provide very high-quality data as well as a good penetration. Both systems have a sensible measurement setup that needs to be considered. The white light interferometry is more suitable for matrix-fiber composites, because the ultrasonic method produces reflection at every interface, even with inhomogeneties such as matrix-fiber composites. The white light interferometry could also be used for a more intense MRO-check, e.g. after 100 hours of flight. The LIDAR sensor is suitable to determine if all the components exist and are in the right place. We want to highlight here, that the LIDAR sensor can lead to absorption or strong reflection at certain orientations or surfaces. To eliminate the cause for this, we need to install a suitable illumination and orientation of the LIDAR sensor, which needs to be tested experimentally. This sensor could be used in combination with a handheld system by an employee. This task could also be done by the camera system and a neuronal network, but it will be under specific circumstances, e.g. illumination, less suitable. The eddy current method and the microwaves could be used if inspection of metal parts in the intense MRO-check is needed. It is to consider here, that both methods have low penetration and less depth information so an inspection with the white light interferometry is more suitable. We didn’t regard the thermography anymore, because we don’t want the vehicle to be thermally loaded, also the penetration is less. The shearography can have too high uncertainties through a possible overlapping of damages in case of complex geometries and therefore won’t be considered here. The x-ray tomography needs too high effort for a quick pre-flight check and the needed external radiation protection provides extra costs and raises the complexity of the system so that we neglect this method for the vehicle inspection. For all systems which we suggested here, it is necessary to check in practical tests with real construction parts of the vehicles whether the advantages are useful or the disadvantages lead to problems during the inspection.

6. Conclusion and outlook

In this work, we analyzed motion and sensor concepts to investigate possible pre-flight check methods for vehicles in unmanned urban air mobility. For this purpose, we conducted a value-added analysis and added the best values to a hybrid concept for the needed pre-flight check. This can be done in two steps. First a holistic scan of the drone with a camera with two ring lights for the illumination. Then a more specific inspection of the parts where failures were detected by the camera with white light interferometry. It needs to be considered that the theoretical investigations in this work can’t show up the exact reality. In the practical testing, other results might occur so a practical investigation is necessary to prove the here investigated concepts. Further, the interaction of the chosen components on the vehicles’ surfaces and volumes can be proofed and optimized.

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