Assessment of Optical Markers for On-Board Autonomous Localization of eVTOLs during Landing

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***Abstract*—Knowing confidently and reliably your position is the basis for autonomous and safe operations of air taxis in the emerging urban air mobility market. Especially during landing satellite based navigation alone is not sufficient. Additional accuracy and integrity are required. Computer vision can profit from the information rich visual environment and is potentially suited to provide localization but algorithms need to adhere to the strict requirements in manned aviation. In this paper we propose an optical localization system on the basis of the artificial fiducial ArUco markers similar to QR-codes for the landing of eVTOLs. The proposed localization system consists of a landing pad design based on ICAO regulations enhanced with an arrangement of markers that should allow localization during approach at any height. The presented system was then evaluated in graphical simulations such as VTK and AirSim. Furthermore, we artificially induced errors into the detection algorithm to test for error detection and correction capabilities. Finally, small-scale real world experiments were conducted to verify our observations. We found that 2 meter sized markers can be detected from as far as 60 meters even under varying weather influences and that centimeter accuracy can be reached although the error increases with distance to the landing pad. Additionally, we can show the validity/suitability of the markers as trustworthy reference points, have reason to believe that detection errors can be compensated within the application and potentially detect integrity violations. While this study reveals the potential of the system and laid the basis for its practical and economic use, it is the starting point for the development of a holistic navigation system that will make use of additional environment information and needs to be verified by large scale real world tests.**

Optical Markers; Localization; Navigation; eVTOLs; Air Taxis; Urban Air Mobility; Autonomous Landing; Computer Vision; ArUco; Integrity

I. INTRODUCTION

Ongoing urbanization leads to a densification in cities and changes the requirements on transportation systems. Many traffic routes in major cities are drastically congested. Aircraft are able to use the third dimension of the city area and may advance the capacity and attractiveness of the traffic system. Electric vertical take-off and landing (eVTOL) vehicles define a new aircraft category and propose many advantages for use in urban air mobility. Nonetheless, they still face many technical challenges to overcome with being safety the highest priority and requiring autonomous operations for the economic success of the business model. Removing the pilot maximizes the payload capacity and counters pilot shortage. As a basis for safe autonomous operations, a clear and reliable localization is required as all further functionality builds up on this. Whereas in cruise flight global navigation satellite system (GNSS) based solutions can be sufficient for localization, final approach and touch down are critical flight phases, which require high precision, additional integrity as well as redundancy and must potentially work even in the event of GNSS signal loss. Classical radio guidance systems for landing are expensive and are not feasible for a big number of vertipads. Satellite or ground based augmentation systems (SBAS/GBAS) could improve GNSS performance. Nonetheless, decentralized landing locations and urban operations are a challenging environment for landing systems. Optical systems have shown to be a promising approach to collect various environment data and could either be used for augmenting GNSS solutions or provide an additional independent solution. For navigation and localization, however, unique and well identifiable reference objects/points to which a relative position can be calculated are needed. Fiducial markers have an encoded binary pattern and qualify as such reference objects. While they have been used for various navigation tasks, they have not been implemented for manned aviation and especially for eVTOLs yet.

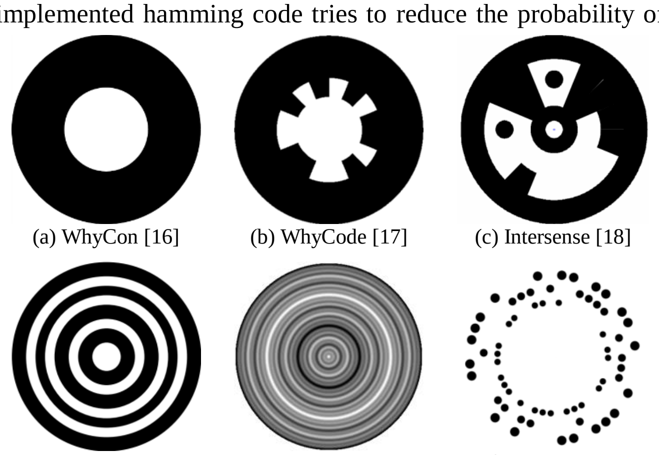
In this paper, we assess the usability of fiducial optical markers as part of a concept for optical localization during landing of eVTOLs. For this, the remainder of the paper is structured as follows. First an overview of fiducial marker

This paper is based on the author's previous work [1] systems, their detection and navigation use is given. Second, the design of the localization system is presented and the special needs of the application are depicted. Finally, the function and performance of the solution is evaluated in simulations and real world tests.

II. CURRENT STATE OF THE ART

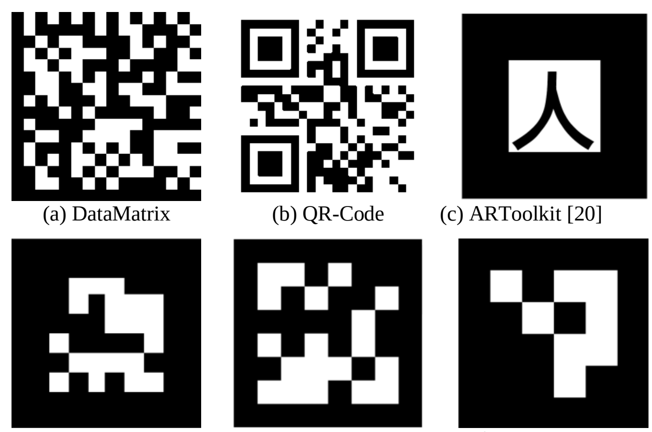
A fiducial optical marker can generally be considered as an artificial object placed in the environment which follows the principles of a predefined model [2]. Hence, they are artifacts that can easily and reliably be detected and with their inner structure offer an interpretable meaning. Such markers have found their application in many different fields. One common application is making use of the ability to store data in a binary encoded pattern. Furthermore, optical markers are used as environment reference points, i.a. in augmented reality applications, video editing and robotics. Detailed overviews of marker systems can be found in [3–6]. Some examples of markers are shown in Fig. 1 and 2. Generally, marker systems may be divided into circular and rectangular markers. While circular marker designs are considered to be more robust against motion blur and occlusion tolerance [7,8], rectangular markers can encode a larger data payload and have found extensive application. Markers such as DataMatrix or QR-Code are used only for data transmission. They encode data through the cyclic redundancy code respectively the reed-solomon error correction [9]. These markers are not suitable for being used as an optical reference because they were not developed for being detectable from a wide array of perspectives but primarily from a straight frontal view and do not provide appropriate reference points for localization [10]. For rectangular optical reference markers it is usual to have a black rectangular border on a white contrasting background. While the ARToolkit from Kato and Billinghurst uses any black-white pattern such as logos inside the rectangle, Fiala's ARTag encodes an individual ID into it [10,11]. The implemented hamming code tries to reduce the probability of marker-confusion to a minimum. Based on the ARTag the AprilTag optimizes encoding and detectability [12]. The algorithm of Garrido-Jurado et al. makes it possible to create user-defined marker dictionaries which further optimize the inter-marker-distances of their codes (i.e. the overall number of bits that markers are different from each other in a given set) [13]. Mostly marker dictionaries with markers that encode 4x4 or 5x5 bits are common. The current code generation makes use of mixed-integer programming. Together with a pipeline for detection this concept is implemented in the open source ArUco-library and integrated into OpenCV [14,15]. Because of their broad use and accessibility the ArUco-markers will be used in the further survey. They can be seen as a reference state of the art system.

To understand its advantages and limitations for the application of localization, it is necessary to know the steps in the detection pipeline. The following description is based on the steps described in [13]. In general, the algorithm first finds contours of possible markers and then reads the code of each marker candidate to determine whether a valid marker has been found. The contours are detected in a two-step process. Initially the image is segmented into two classes, i.e. the colored input image is reduced to a binary image only. This reduction is made through a local thresholding-method. Consecutively contours are detected by the algorithm of Suzuki and Abe which result from following connected pixel chains [21]. Finally the contour can be simplified by Ramer-Douglas-Peucker such that the contour is smoothed but its underlying form is preserved [22]. Only contours with four edges are considered, to further filter the candidate contours. A verification of contour-candidates is conducted by reading the binary code. The marker bits are read by averaging multiple pixels and by omitting values from the border of the bits as they can have an influence from neighboring bits. Finally, the edge point image coordinates of the markers as position references can be refined by different methods to



(a) WhyCon [16] (b) WhyCode [17] (c) Intersense [18]
(d) CCTag [7] (e) Fourier Tag [19] (f) Rune Tag [2]

Figure 1 Circular marker systems



(a) DataMatrix (b) QR-Code (c) ARToolkit [20]
(d) ARTag [10] (e) AprilTag [12] (f) ArUco 4x4 [13]

Figure 2 Rectangular marker systems

subpixel accuracy. As the 3D-position of these edges as references is known beforehand the calculation of the camera/aircraft position becomes the well-studied perspective-n-point problem (PnP). The basis of this is the equation projecting the 3d-point $\mathbf{p}_r^i$ into the image plane $\mathbf{p}_s^i$:

$$\mathbf{p}_s^i = \frac{1}{z_0}\mathbf{KRTp}_r^i \quad (1)$$

K is the intrinsic matrix of the camera, **R** and **T** the camera rotation and translation and z_0 a yet undetermined factor representing the distance along the ray. Generally, **RT** can be calculated with more than four correspondences. The resulting over-determined system is optimized using the re-projection error and a levenberg-marquardt algorithm. A detailed description of the algorithm can be found in [23].

While markers as artifacts are used in many different applications they have not yet been used for manned VTOLs and aircraft systems for landing. Nonetheless, existing evaluations for unmanned aerial vehicles imply potential for autonomous landings but have shortcomings that further motivate our research and development. [24–27] show that localization and guidance by a self-developed marker is feasible. Furthermore, [28] compares different methods for landing found in literature but reasons that marker detection by neural networks is the most precise and fastest method. Commercial systems and private individuals also use markers of different size to conduct autonomous landings of drones. However, they only make use of one marker at a time to calculate the ego position. If one is far away from the marker in relation to its size, the edge points of the marker are close together in the image plane, which can induce ambiguities in position calculation and minor degradations in edge point detection can lead to large reconstruction errors in the calculation of the relative ego-position.

III. System Design

Based on the ArUco marker system, we propose a positioning system with multiple markers that can be used to exemplarily validate the suitability of markers for use during VTOL landings. The requirements identified and presented in the following serve as a basis for the design but also as evaluation parameters. We followed a top-down approach, because this does not require any a-priori knowledge about system properties yet is suitable for assessing the function. Performance Based Navigation is a recent holistic approach that determines the higher-level requirements for an aeronautical navigation system in terms of accuracy, integrity, continuity and availability [29]. We define these values equivalent to Required Navigation Performance SBAS/GBAS Approaches. The approach procedure categories set different decision heights and minimum visual ranges depending on the confidence level in the system. These minima allow the pilot to independently verify the functioning of the system. If a fully automatic landing system is to be used, there is no pilot monitoring, thus the system requirements are equal to systems without decision height. However, this does not mean that no optical system can be used. In fact, it can even take over or supplement the position determination when a decision height of a GNSS system is reached. VTOLs compared to airplanes have some special flight characteristics. These vehicles can hover stationary, have a high maneuverability and can approach with low vertical and horizontal speeds. The Federal Aviation Administration therefore regularly permits a reduction in the visibility minima for IFR (Instrumental Flight Rules) approaches by helicopters by up to 50 % [30].

These considerations already allow some estimations of the boundary conditions of the optical positioning system and thus of the requirements. Typical approaches with GNSS equivalent to instrumental landing system category I have a minimum decision height of 60 meters (200 ft). Non-precision approaches have a Minimum Decision Altitude (MDA), below which aircraft may not descent during approach as long as the runway is not in sight. For example, when approaching with Non Directional Beacons, the MDA is set to a minimum of 350 ft (approx. 100 m) [31]. Considering mostly reduced minima for helicopters, it therefore seems appropriate to design the optical positioning system for a maximum height of 60 meters. Above this height, it is assumed that a SBAS/GBAS augmented GNSS positioning system alone is sufficient. Although requirements for the accuracy of an GBAS approach equivalent to CAT IIIb have not been finalized yet, defining a lateral navigation system error of maximum 5 meters and vertical 2.9 meters for the optical system seems reasonable (compare i.a. [32]).

During the final approach, it is practical to center the VTOL at the beginning above the landing site in hovering flight and then to reduce the altitude. This minimizes the noise pollution and the required safety space around the landing area compared to an inclined approach. Normal helicopters usually perform an angled approach, as this supports autorotation in the event of an error. Since no single component can lead to a failure with the distributed electric propulsion concept, a vertical final approach of VTOLs should be safely feasible. Whether the landing procedure also safely meets specific aerodynamic requirements such as the prevention of vortex ring conditions is unclear and goes beyond the scope of this paper and is therefore not considered here.

There are several scenarios for the use of the optical positioning system: On the one hand, it can initially support the pilot during visual approaches as an augmenting system, as in the near future, a safety pilot will initially always be necessary. On the other hand, it may be used as a supplement to GNSS as an additional and independent data source to improve integrity and accuracy so that the systems are jointly capable of providing navigation data for automatic landing. In addition, the optical system could also provide a fully GNSS independent position. The presented concept considers the optical positioning according to the last option. Since this leads to the highest requirement for the system, the investigation covers the other applications as well.

Landing sites for helicopters are defined by ICAO Annex 14 Vol. 2 [33]. They can be circular or rectangular. Touchdown and lift-off area (TLOF) should not be smaller than 0.83 to 1 times the diameter of the rotor and be marked with a white circular ring of 0.3 meters stroke width. Touch down point, however, has to be marked with a yellow circular ring of 0.5 m width and should have half the dimensions of the rotor diameter. Lastly, a landing site has to have a heliport identification marking, i. e. the "H" whereas this might be changed to a "V" or other markings for eVTOL applications in the future. To this time, the largest air taxi concept known has a diameter of 13 Meters so therefore it is recommended to have a TLOF of at least 15 meters [34]. Within this surface and considering the existing markings, the fiducial markers should be positioned in such a way that they can be recognized from any position the flight taxi can be in during landing and such that a position can be calculated. In addition, the existing heliport markings could also be used for localization but this is postponed to future research (and has been surveyed previously with mixed results).

When a VTOL lands, the position must be reliably determined by the optical system between a height of 60 meters and touchdown. The field of view of a camera covers the ground between a height of a few centimeters and many meters. For each height, markers must be arranged and visible in such a way that they enable the position to be determined in accordance with the requirements. This wide altitude range makes the landing a special environment. In order to detect a marker and read its binary code, it must have a minimum size on the image plane (in pixels). These relationships define a minimum size for markers so that they are still recognizable at a certain height. The maximum size of a marker, on the contrary, is solely limited by the fact that it should be located within the field of view. Since rotations in particular can significantly shift the field of vision, a zone at the edge of the field of view must be kept free. Furthermore, it is to be assumed that the camera can be traced and is aligned with the touchdown point. Simulations and tests show, that the minimum size of a 4x4 marker on the image plane should have at least 15-20 pixels edge length to be reliably detectable.

Between the TLOF and touchdown point marking up to nine markers with an edge length of up to 2 meters fit easily. Considering the optical geometry of common industrial grade cameras (the camera taken as a reference has 1312 x 1082 pixel and 8 mm focal length) it is assumed that the large markers are reliably detectable at a height of 60 meters. These big markers, however, leave the field of view when coming closer. At low heights the challenge is to always provide enough visible markers in the field of view. Two proposals of marker arrangements are shown in Fig. 3. They are optimized to provide enough detectable markers at any perspective and height. These arrangements are first used to validate applicability of markers. Final landing pad design will probably be different such that the markers are least visually distractive. Also conformity with regulations needs to be further investigated but this is postponed to future research.

As already described, it is possible to calculate the position of the camera (and hence of the eVTOL) with the detection of just one marker. However, being far away from the marker this can lead to ambiguities and imprecision as little variations in the measurements lead to big variations in position. Using multiple markers at once which are spread along the image plane can potentially improve accuracy and robustness. In addition, wrongly detected or confused markers could be identified and omitted for position calculation.

IV. EVALUATION

The proposed system is intended to be a hypothesis of the functioning and suitability. By evaluating the system we are able to draw conclusions about its validity and the suitability of optical navigation systems employing markers for the eVTOL landing scenario. First, the proposed system was evaluated in simulations and additionally the results were verified by an experimental set-up under real world conditions. For the first step, the Visualization Toolkit (VTK) as a graphics engine was initially selected due to its close integration into OpenCV to validate the graphical geometry. As an example, the images in Fig. 3 were taken in this simulator. However, the generated images mostly represent perfect conditions as there is global illumination and

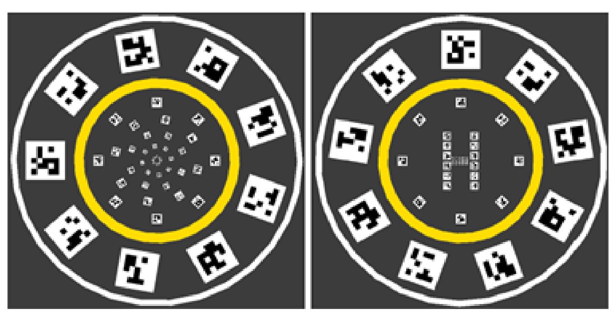


Figure 3 Proposed landing pad designs and marker arrangements

environmental influences, which make detection of the markers in real world scenarios more difficult, are not simulated. Thus, subsequently the AirSim Simulator based on the Unreal4 Engine was used to generate more realistic images and simulate environmental influences, e.g. weather. Real world test were conducted statically with a camera previously used in flight tests facing a wall of markers. This cascading evaluation makes it possible to assess the influencing factors to the localization algorithm and evaluate their individual contribution. Real world flights with our research aircraft were conducted with forward and downward facing cameras across cities, terrain and helipads. This enables detailed assessment of the environmental conditions of eVTOLs and the development of further computer vision algorithms in the future. We make this dataset publicly available[1].

A. Marker Detection

In the VTK simulation all nine 4x4 outer markers could be reliably detected below heights of 60 meters even if their size has been reduced to 1.5 m. It is to note, that above this height there is no sudden drop in the detection rate but a steady decreasing number of detected markers. It has been found in the simulation however, that 5x5 markers are at 60 meters only reliably detected if they have an edge length of at least 2 meters. The outdoor test series verifies this. As the marker size has been reduced to 0.8 m edge length here due to practical reasons, a position can always be calculated under 40 meters distance. That means a standard scaled 2 meter marker should be reliably detected from 60 meters. Whether there is degradation in the detection rate when weather phenomena such as dust, mist and fog are evident was tested with the AirSim simulator. As can be seen in Fig. 4, even with quite strong visual impairment, in those simulations still about half of the markers can be detected at heights of 60 meters. With this detection rate a position calculation is possible. These results suggest that weather phenomena do only have minor influence on the availability of the optical positioning solution. However, it is not clear to which extend the simulated weather phenomena are representative of real weather conditions. Further investigations are therefore required in the future.

Figure 4 left: no weather; right: snow, dust and fog combined, 4 out of 9 markers detected

[1] https://www.tu-braunschweig.de/iff

B. Edge and Point Detection

Marker detection is followed by a refinement of the vertices. The accuracy of the refinement directly has an effect on the position calculation. In the VTK simulation it is possible to get the ground truth data for the edges and therefore the performance of the algorithms can easily be tested. The refinement method based on the cross product, using contour points and the algorithm from the AprilTag library as implemented in OpenCV were tested [35,15,36]. The performance of the algorithms can be found in Tab. I. While the rest even induced an additional error, the "AprilTag" method of Wang and Olson reduces the mean pixel error of edge detection to 0.19 pixels.

TABLE I. PERFORMANCE OF EDGE REFINEMENT ALGORITHMS (PIXELS)

	No refinement	Cross product	Contour	AprilTag
Mean	1.10	1.9	0.97	0.19
Std.-Dev.	0.05	0.34	0.01	0.04

Calculating the position with the refined edges, the re-projection error is utilized as the error function to be optimized. It expresses how well the calculated position represents the detected position of points in the image plane. The final position estimation of the points on the image plane can be evaluated if ground truth is available by comparing the re-projected points from calculated and true ego-position. It is observed that the error induced by edge detection is permanently bigger than the absolute re-projection error. Therefore, the position calculation by the PnP algorithm can compensate for error in edge detection such as that a mean absolute edge detection error of 0.1 pixels is achieved. This distribution of error portions is not universally valid but leads to the conclusion that subpixel refinement methods as well as the arrangement of the markers do not induce relevant additional errors.

C. Position Solution

The position solution error in VTK simulations for a slightly off centered corkscrew trajectory is presented in Fig. 5. This trajectory was chosen as a reference trajectory as this is

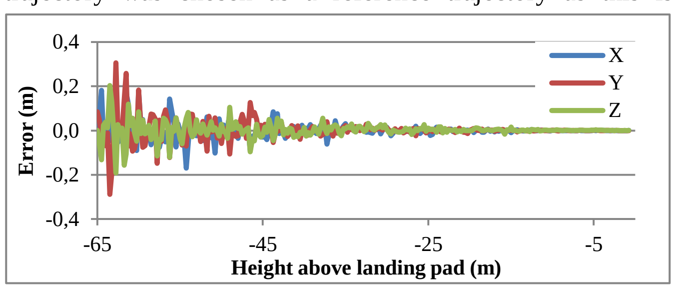


Figure 5 Positional error on reference trajectory

Figure 6 Experimental setup

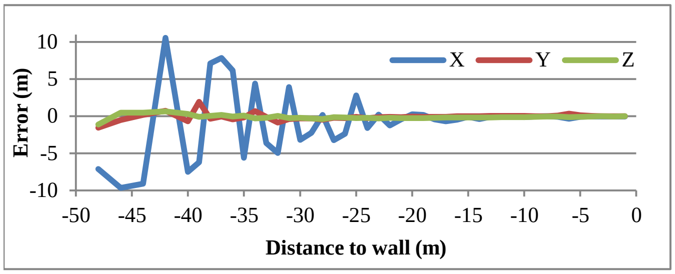


Figure 7 Positional error in real world experiment

covering many diverse positions that are possible during an approach. Note that all poses are depicted in the right handed landing pad coordinate frame. As the x- and y-axis lay along the landing surface and z-axis goes into ground, the aircraft height is denoted with a negative sign. With its ideal projections these results in the simulator can be seen as the upper boundary of what can be achieved in reality. The absolute error does not exceed more than one meter at any height and is decreasing with decreasing height. These deviations surpass the requirements of 2.9 meters vertically and 5.9 meters laterally. Therefore, this method is principally suitable for supplying accurate positions during eVTOL landings.

In addition to the camera position, its orientation is calculated as well. Although this paper focuses on the positioning information the maximum error does not exceed 0.8 degrees in simulations. Further investigation could utilize this information for drift compensation and integrity checks.

The outdoor test case scenario has a reduced and downscaled marker set-up as depicted in Fig. 6. Ground truth position was measured manually. As can be seen in Fig. 7, measurements in y- and z-direction with a maximum deviation of less than 2 meters were obtained, which is inside the requirements. The error in x-direction oscillates above distances of 20 meters up to 11 meters. As this does not happen along the y-direction (along which the markers are distributed as depicted in Fig. 7) it seems favorable to distribute markers in all directions on the viewing plane, as is the case in our proposed landing site design (Fig. 3).

D. *Integrity*

The key proposed advantage of fiducial markers towards other landmarks is that they provide a uniquely identifiable reference. As depicted, this is achieved by the binary code which is read and compared to the expected codes. This code can be of variable length, e. g. 4x4 or 5x5 (16 respectively 25 bits). The individual codes must meet a number of requirements and should therefore be chosen deliberately. On the one hand, it is important that they are clearly distinguishable from the environment. No object should be mistakenly identified as a marker. Furthermore, a marker must not be rotationally symmetrical so that its orientation can be clearly determined. On the other hand, markers must be designed in such a way that they cannot be confused with each other. The similarity of codes is indicated by the so-called hamming distance τ. It measures the number of different bits between two codes of the same length. Because markers can be oriented in four different ways, the hamming distance of a marker is the lowest one resulting from rotating the markers to each other. Finding several marker codes that meet the above requirements and maximize the hamming distance to each other even under rotation is complex. The exact procedure of the generation is not relevant for the use and evaluation of the codes and is therefore not described in detail. However, the minimum hamming distances of the generated codes within a directory of markers can be determined directly and are presented in Tab. II.

TABLE II. HAMMING DISTANCES AND ERROR PROBABILITIES OF MARKER SETS

	4x4	5x5	6x6
$\tau_{25\ markers}$	5	8	14
$\tau_{50\ markers}$	4	8	13
$\tau_{100\ markers}$	3	7	12
wrong bit detection rate for confusion	25%	32%	36%
confusion probability (p=0.1)	6.8E-02	2.3E-03	2.5E-05
false positive detection probability	3E-03	6E-06	3E-09

To mistake one marker code for the other, 25 % of a 4x4 code must be misinterpreted. If the bit-errors are considered independent and identically distributed, one can calculate the probability that the critical hamming distance is reached (compare [10]):

$$p_{confusion} = \sum_{n=\tau}^{l} p^n (1-p)^{l-n} \frac{l!}{n!(l-n)!} \tag{2}$$

p is the probability of the false detection of a single bit and l the length of the code. Since the false detection probability cannot be specified and depends on the boundary conditions, no generally valid quantitative values can be calculated. Assuming a false detection probability of p = 0.1 (which is freely chosen but seems reasonably above true probability), the probability is then that one detected marker is actually another, for the 4x4 code at most 6.8 %. The probability with longer marker codes decreases significantly. A 5x5 marker already possesses a probability of confusion of only 0.23 %. It is assumed that the absolute numerical values are even lower in reality, since the false detection probability of individual bits is already minimized (see description of detection pipeline).

The probability to hit a marker code just by guessing is:

$$p = n_{Codes} \times \frac{4}{2^{l}} \quad (3)$$

and is calculated in Tab. II as false positive detection probability. Thereby each pattern is regarded as equally probable. In reality, however, rectangular patterns tend to occur with lower entropy [10]. There are usually larger continuous monochrome areas. The marker codes are generated in such a way that as many bit variations as possible are present within a marker. This further reduces the probability of false positive marker detection. In the context of VTOL localization, failing to detect a marker is not an integrity risk. It is only required to identify a sufficient number of markers in order to determine a position.

In summary, the methods for coding and identifying the markers promise a high level of confidence that the correct marker has actually been identified for a detected marker. As 5x5 marker codes increase confidence levels significantly, shorter codes should not be used.

Although for concrete and significant conclusions, a more comprehensive and defined test design is necessary, in all simulations and real world experiments error generating marker detections were not observed. To test the potential of the solution for integrity detection and correction capabilities, an experiment was conducted where the coordinates of one marker (out of nine) were artificially swapped, degraded and faked to simulate marker confusion and outlier handling. Tab. III shows the accumulated re-projection errors for the individual markers and the position error. Due to an imposed corner point error of 10 pixels in each image direction of a corner point of the marker with ID 8, it can be seen that the marker has a significantly increased corner point re-projection error compared to the other markers. Thus this outlier can be easily excluded. The position result with a single outlier deteriorates slightly. Although a mistaken marker does not result in a position result that can be used, this is also reflected in the average rear projection error. All markers have a very high re-projection error but the mistaken marker has a value about 10 times as high as the other markers, so it can be also excluded. After exclusion, a correct solution can be determined, whereby the position error only deteriorates by 0.03 meters compared to the position calculation with 9 markers. This shows that both outliers and mix-ups can be detected and corrected.

TABLE III. TEST RESULTS FOR ERROR DETECTION AND CORRECTION CAPABILITIES

	No error	**Edge point deviation**	**Confusion**	**After exclusion**
Position error [m]	0.07	0.5	27	0.10
Abs. reprojection error [m]	0.16	2.3	73	0.16
Rep. error (pixel) for marker 0	0.77	1.6	1040	0.71
1	0.07	0.6	426	0.08
2	0.01	0.1	2260	0.01
3	0.00	0.2	12308	0.01
4	0.01	0.1	18425	0.01
5	0.01	0.2	10967	0.01
6	0.01	1.5	1703	0.01
7	0.02	3.7	769	0.03
8	0.05	178.4	146553	

E. Conclusion

This paper has investigated the performance and suitability of an optical concept for position determination using fiducial markers during the approach of eVTOLs. Using ArUco markers, we developed a method and proposed a landing site design to localize eVTOLs during landing. In simulations and small scale real world tests the performance of the algorithm was evaluated and compared to identified requirements.

Results indicate that the vertical distance estimation is accurate both in the simulator and under real world conditions. An operational limit is defined by the maximum altitude above ground up to which reliable detection of the markers is possible. In addition, the position solution is dependent on the flight altitude. At low altitudes the error is in the centimeter range and increases with increasing altitude. The rectangular markers can be used as clearly referenceable spatial points in the landing field. Confusion between different markers as well as wrong detection is unlikely and can be corrected.

In principle, the proposed optical positioning system is suitable for estimating the position of eVTOLs during landing. Further investigations under real world conditions are necessary to test its universal applicability. A true scaled and asphalted landing site as a testbed could validate the system with additional confidence. Furthermore, there is additional environment information that could potentially be used for navigation (such as ring markings) which should be investigated in further research. On the way to certification and application a thorough quantitative analysis of PBN parameters is required. Nonetheless we laid the basis for the practical and economic use of such a positioning system.

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