Simulation based Analysis of High Precision UAV Tracking with Robotic Total Stations

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Abstract: This contribution presents the concept of the TrackDrone project, which aims at high-precision determination of UAV-trajectories based on total station measurements, and the implementation of a Monte Carlo simulation to assess the potential of the proposed concept. The functional model considering the latencies exhibited by the total station as well as the setup accuracy is presented. This work investigates only the 3D position of the UAV and lays the foundation for research towards the 6-DOF trajectory. In addition to describing the implementation of the simulation, a sensitivity analysis with respect to the extrinsic temporal calibration parameter is performed showing the dependence of the resulting RMSE on the uncertainty of the calibration parameters and the velocity.

1 Motivation

Measurements from kinematic platforms such as UAVs are an integral part of modern surveying. Such multi-sensor systems require trajectory information to successfully geo-reference the data acquired by the imaging sensor, e.g. an airborne laser scanner (ALS) or cameras. Therefore, the need for reliable and accurate trajectory data of multi-sensor systems is present in a wide range of applications, ranging from infrastructure monitoring via robotics to photogrammetry. Improving the accuracy of the estimated trajectory accuracy is the primary objective of the TrackDrone research project, which uses a decentralized multi-sensor approach, where the involved sensors are spatially separated in a ground segment and a kinematic segment. This enables new possibilities for determining the position and orientation of the measurement platform by combining Robotic Total Stations (RTS), Image Assisted Total Stations (IATS), inertial measurement units (IMU), and imaging sensors like cameras or laser scanners.

RTS are often selected to measure trajectories of kinematic platforms, either to assess the accuracy of a GNSS/IMU-based navigation solution or as a measuring instrument for determining the trajectories themselves (BLAHA et al. 2012; PARAFOROS et al. 2017; ROBERTS & BOORER 2016). However, there is a lack of comprehensive research on the capabilities of RTS in scenarios, when high speeds and distances of these platforms relative to the RTS are taken into account, as most research is limited to slower near-range use cases (KÄLIN et al. 2023; TOMBRINK et al. 2023).

The main motivation is to improve the accuracy and reliability of existing methods, such as GNSS/IMU-based trajectory determination. The proposed method is independent of GNSS availability, and achieves higher accuracy. To achieve this, all sensors mounted on the kinematic segment are used and combined with the RTS data from the ground segment, finally resulting in an integrated trajectory estimate.

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The involved systems and the overall concept of the described approach are schematically depicted in Fig. 1, where the GNSS/IMU-based trajectory of a UAV is improved by the polar observations of two IATS, the photogrammetric measurements based on the integrated telescope camera and the imaging sensor mounted on the UAV, to derive a 6-DOF trajectory.

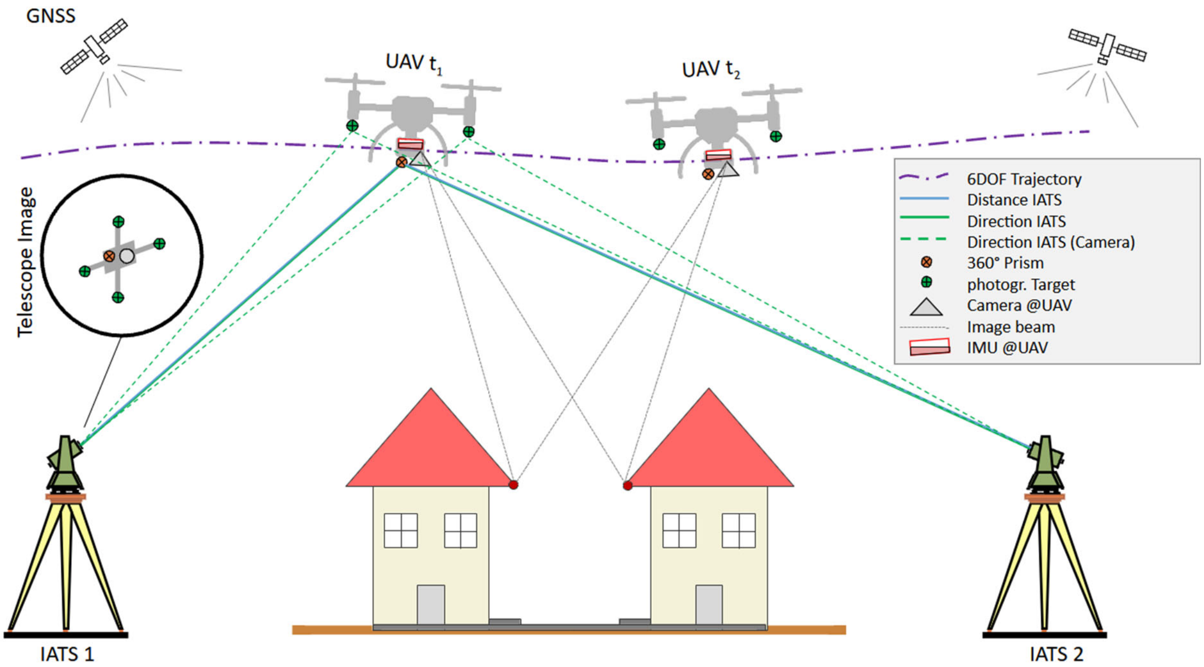

Fig. 1: Concept for the integrated trajectory estimation in the scope of TrackDrone

At the current stage of development, the system is limited to the ground segment, i.e. an accurately time referenced 3D trajectory of the UAV is measured by multiple IATS, and the orientation of the platform can be extracted from the recorded videos of the coaxial cameras of the used IATS, comparable to the investigations of NIEMEYER et al. (2012).

The integration of the onboard-sensors of the UAV will be the main task in the following project phase.

Being in its first year, the project focuses on the position component of the 6-DOF trajectory of the UAV. The integration of the orientation of the UAV will be emphasized in the next phase of the project.

The focus is set here on a Monte Carlo simulation to assess the achievable accuracy of the observed trajectory, considering the significant effects originating from RTS observations that have an impact on the position of the UAV.

The remainder of the article is structured as follows: Section 2 reviews the related work and introduces the methodological details as well as the functional model of the employed numerical simulation. Section 3 presents the results of the implemented Monte Carlo simulation and shows the possibility to perform a sensitivity analysis based on the simulation, focusing on the temporal calibration parameters. Section 4 summarizes the contents of the contribution and gives an outlook on further research activities.

2 Related work and Methodology of the Numerical Simulation

The Monte Carlo simulation or Monte Carlo method is a common tool for the propagation of distributions (BIPM et al. 2008). Due to its flexibility and easy implementation, the Monte Carlo method enjoys great popularity for the assessment of uncertainty in measurement scenarios. The general method has been widely adopted in many scientific fields to numerically approximate the probability density functions of an output quantity and as such has already been employed to assess the potential of geodetic measurement configurations by various sources. NIEMEYER et al. (2012) use a Monte Carlo simulation to assess the potential of IATS based observations for determining the exterior orientation of a UAV. The simulations are based on the observation of spherical targets, mounted on the UAV, in the camera images given by the IATS.

ULRICH et al. (2013) uses Monte Carlo simulations to derive the probabilistic model, which is necessary as input for a Bayesian filter, for a Leica laser tracker from a MC-simulation. The reason for choosing Monte Carlo simulation over variance propagation is due to its simpler implementation and avoidance of linearization errors (ULRICH et al. 2013).

In VAIDIS et al. (2023), a Monte Carlo simulation is used to investigate the uncertainties arising from a multiple RTS setup on the 6-DOF trajectory of a kinematic platform with multiple reflectors mounted. The Monte Carlo simulation is used to identify the most relevant input parameters and quantify their effect on the observed trajectory, quite similar to the objective of this work.

In contrast to existing work, the implemented simulation in our work considers a different scenario and takes into account additional impact factors. One focus of the presented simulations is the thorough investigation of the impact of the temporal calibration performed according to THALMANN & NEUNER (2021) on the RTS based positioning of a UAV. In THALMANN & NEUNER (2021), the latencies exhibited by the total station are separated into the extrinsic latency δt^d, which expresses the time delay between the execution of distance measurements of an RTS and the provision of a timestamp within a known timeframe and the intrinsic latency δt^a, which describes the time delay between the distance measurement and the horizontal angle measurement. For this work, the formulations presented in THALMANN & NEUNER (2021) were extended to match the three-dimensional case. This requires the introduction of a second intrinsic latency δt^z, expressing the delay between the distance measurement and the zenith angle measurement.

In order to consider the accuracy of the temporal calibration procedure, new investigations had to be carried out to determine the values δt^d, δt^a, and δt^z for the Leica MS60 as well as their corresponding standard deviation.

The functional relationship between these latency parameters and the three-dimensional coordinates of the trajectory is given in eq. (1), which shows the polar measurement formula for kinematic scenarios, considering individual measurement times for the horizontal angle $R(t_a)$, the zenith angle $Z(t_z)$ and the distance measurement $D(t_d)$.

In general, a fictional trajectory of a kinematic platform $\bar{x}(t_j)$ serves as the first input for the simulation. Based on this trajectory, the polar observations of a total station at a specified position $\bar{x_s}$ with an orientation unknown o_s are calculated. This happens for all i specified total stations.

$$x(t_j) = x_s + D(t_d + \delta t^d) \cdot \cos[o_s + R(t_a + \delta t^d + \delta t^a)] \cdot \sin[Z(t_z + \delta t^d + \delta t^z)]$$

$$y(t_j) = y_s + D(t_d + \delta t^d) \cdot sin[o_s + R(t_a + \delta\, t^d + \delta t^a)] \cdot sin[Z(t_z + \delta t^d + \delta t^z)]$$

$$z(t_j) = z_s + D(t_d + \delta t^d) \cdot cos[Z(t_z + \delta t^d + \delta t^z)]$$

Eq. 1: Functional model of the Monte Carlo simulation

The following influencing parameters in eq. (1) are treated as uncertain measures in the simulation: $D, R, Z, \delta t^d, \delta t^a, \delta t^z, \bar{x}_s$ and o_s. For the Monte Carlo simulation, the statistical distribution of these parameters of the functional model has to be specified. While some statistical characteristics are well known, others need to be estimated in laboratory investigations. The resulting mean value and standard deviation of the corresponding normal distribution of each parameter serve as input values for the simulation (SOKOLOWSKI 2010).

In the simulation process the influencing parameters are obtained by adding to the nominal values a random noise component sampled from the individual distributions. If these modified parameters are then used to calculate the observed trajectory (eq. 1), a realization of the trajectory is obtained. By repeating this process *n* times, conclusions can be drawn about the underlying statistical distribution of the observed trajectory. This leads to the possibility of estimating a mean value and standard deviation for every position of the trajectory.

For a correct Monte Carlo simulation, the total number of iterations *n* must be sufficiently large to enable a reliable evaluation of the resulting output values and of their uncertainties. With computationally small scenarios, such as the RTS based trajectory generation, the value *n* can be chosen almost arbitrarily high. Investigations have shown that the simulation converges after below 1000 iterations. Therefore, *n* is set to 1000 in this study.

Based on the *n* realizations the position-dependent *Root Mean Square Error* (RMSE) of the trajectory is calculated. Since the resulting RMSE value for each point of the trajectory depends on several factors, such as the distance to the IATS, the direction and value of the motion vector as well as the geometric configuration, the representation of these RMSE condensed to single numbers is challenging.

This is why the result of the simulation is illustrated as a 2D-plot, which shows color-coded the RMSE for every point of the trajectory.

While for some cases the main interest might be the resulting statistical characteristics of the coordinates, a great opportunity of the Monte Carlo simulation is the ability to perform a sensitivity analysis. This is achieved by varying single parameters while keeping the other ones unchanged. In this study, we focus on the sensitivity with regard to the extrinsic latency. Based on that knowledge, decisions regarding the required accuracy of the estimation of this parameter can be made on a factual basis.

3 Simulation results and sensitivity analysis

Fig. 2 shows the 3D-RMSE obtained from the MC-simulation for a trajectory located in the study area in Siegendorf (Burgenland, Austria). The kinematic parameters of the UAV were set to 4 m/s (Fig. 2 - left) and 10 m/s (Fig. 2 - right) velocity and 120 m flight altitude. These high values were chosen to emphasize the achievable accuracy under challenging flight conditions. In this study the UAV is tracked by two RTS. Their location is indicated by a red and black cross respectively in Fig. 2.

The standard deviations of the intrinsic and of the extrinsic latency are set to $\sigma_{\delta t^a} = \sigma_{\delta t^z} = 0.1$ ms and $\sigma_{\delta t^d} = 0.1$ ms respectively. These values are taken over from the temporal calibration results presented in Thalmann & Neuner (2021).

The standard deviations of angle ($\sigma_r = \sigma_z = 0.3$ mgon) and distance measurement ($\sigma_d = 2$ mm + 1.5 ppm) are taken from the datasheet of the Leica MS60, which is the RTS used in the scope of the project. The accuracy for the coordinates and orientation of both RTS in the project coordinate frame is set to $\sigma_{\bar{x}} = 3$ mm and $\sigma_o = 0.3$ mgon, respectively.

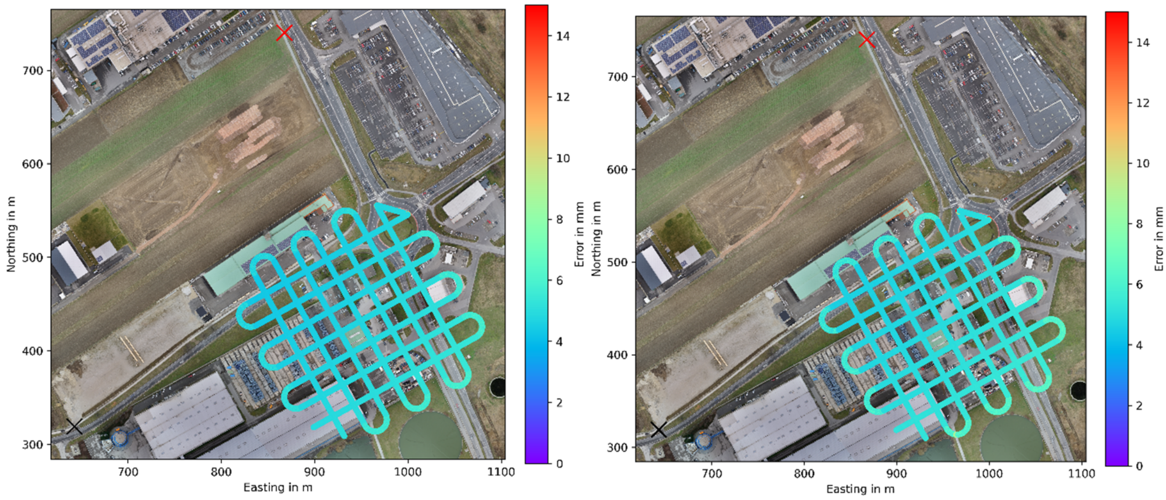

Fig. 2: Results of numerical simulation for a speed of 4 m/s (left) and 10 m/s (right) with two simultaneous RTS (red and black cross) observations

It can be easily seen that the estimated accuracy amounts to about 6 mm for the lower velocity (Fig. 2 left), and for higher velocities (Fig. 2 right) the RMSE reaches a similar level of about 6 mm. The RMSE has an uniform level over the entire trajectory. Slightly higher values are encountered in some turning segments of the UAV located far most away from the two RTS.

This result is promising for the development of an RTS-based UAV tracking procedure, as it competes with or even outperforms the accuracies usually assumed for RTK-GNSS-based trajectory determination. However, while the latency parameters were input quite pessimistically, other impact factors such as refraction or the reflector specific error are not yet considered, which significantly limits the obtained results.

Thus, the comparison shows mainly that an inaccurately determined temporal calibration has a significant, velocity-dependent effect on the observed trajectory.

As an example of sensitivity analysis Fig. 3 shows the same scenario as in Fig. 2 but with a different standard deviation of the extrinsic latency calibration parameter, namely $\sigma_{\delta t^d}$ is set to 1.0 ms, being significantly larger than the previously presented value. However, the value of $\sigma_{\delta t^d} = 1.0$ ms is still a realistic value, given that access to such highly accurate reference data as used in Thalmann & Neuner (2021) is limited and the stability for varying ambient condition of the temporal calibration parameters has not yet been investigated.

To understand the significance of this value, it is important to realize that the error resulting from the uncertainties in the determination of the extrinsic calibration parameter δt^d is directly dependent on the speed of the platform. Meaning that the association quality of a position of the observed platform to a point in time t_j with the measurements of the RTS of a point in time $t_j + \delta t^d$ is strongly influenced by the accuracy of δt^d.

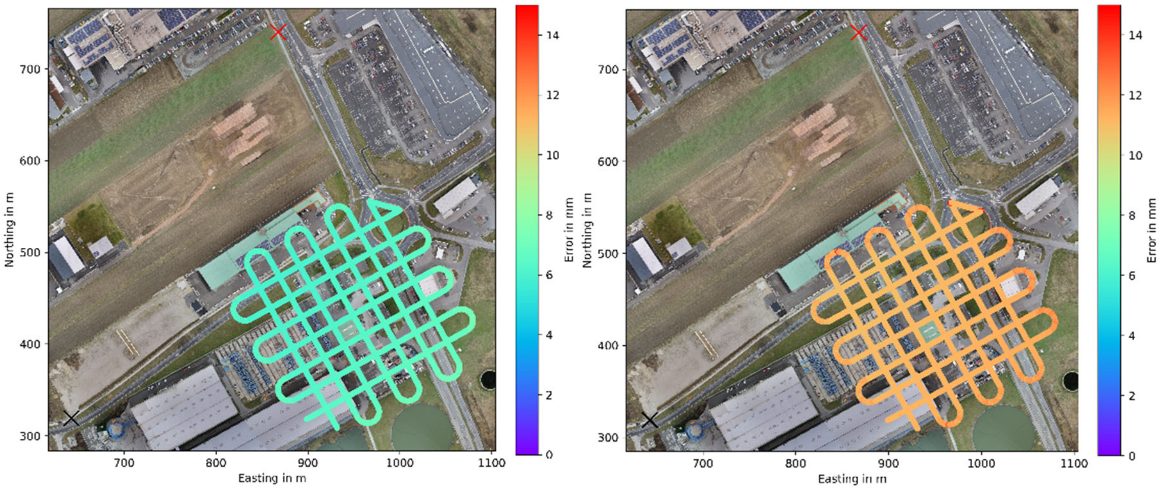

Fig. 3: Results of numerical simulation for a speed of 4 m/s (left) and 10 m/s (right) with two simultaneous RTS (red and black cross) observations, with higher standard deviation of the extrinsic latency parameter

Fig. 3 shows that the result is sensitive to the uncertainty of the extrinsic latency parameter, at least for higher velocities of about 10 m/s. The resulting 3D-RMSE increases to 12 mm respectively 8 mm. This effectively raises the absolute RMSE and the relative change between the different velocities of 4 m/s and 10 m/s.

This allows to draw the conclusion that the temporal calibration is a crucial step and needs to be performed with very high accuracy to be able to use the calibrated RTS for dynamic scenarios as presented in this contribution.

A sensitivity analysis of all included parameters can be performed in an analogue's way, allowing the ranking of the impact of all considered factors onto the observed trajectory.

It needs to be stated here that the simulation is just as good as the underlying model. Therefore, it is necessary to critically assess the simulation results with reference measurements. The background in Fig. 3 shows a small extent of the reference field created within the scope of the research activities. This accurately surveyed reference field allows the verification of the simulation results by comparison of the observed trajectory with the help of over 100 precisely known ground points.

4 Summary and Outlook

In this contribution the aim and scope of the TrackDrone project to enable high precision tracking of kinematic platforms, particularly UAVs, with robotic total stations are presented. Although the project will also integrate onboard sensors of the platform to perform an integrated trajectory estimate by combining the terrestrial and airborne measurements, the current research focuses on the development and assessment of the ground segment, i.e. the IATS observations to the UAV.

To assess the achievable measurement accuracy of such a setup, a Monte Carlo simulation is used to identify relevant parameters and their impact on the overall result as well as favourable configurations. The simulation allows the adaptation of the statistical parameters of every input value and the virtual testing of various measurement configurations to derive the optimal configuration and necessary knowledge about the sensitivity of the observed trajectory with regard to the input parameters. In the contribution, we presented the applied model to calculate the trajectory coordinates from the raw polar measurements, taking into account the temporal calibration parameters, as well as the methodology to implement such a Monte Carlo simulation.

The results presented here focus on the effect of the extrinsic latency parameter as a major factor on the precisely time referenced trajectory. This example shows the large potential of the Monte Carlo simulation and emphasizes the significance of precise temporal calibration of the used total station.

The results show that an accurate determination of the extrinsic latency parameters with a standard deviation of 0.1 ms leads to an almost constant 3D-RMSE in the observed trajectory of about 6 mm, for this particular scenario at a velocity of 10 m/s as well as 4 m/s.

We also demonstrated that a more inaccurately determined extrinsic latency parameter with a standard deviation of 1 ms leads to higher absolute 3D-RMSE of 8 mm at a speed of 4 m/s, with a significant velocity dependent part that increases the 3D-RMSE to 12 mm for a speed of 10 m/s.

Further work regarding the simulation will be the integration of additional effects that affect the resulting trajectory, such as the refraction effect on the height and the impact of the 360°-prism. Additionally, an extensive investigation regarding the effects of several input parameters on the observed trajectory will be performed to correctly assess the requirements on individual components, such as accuracy of the temporal calibration procedure, for a desired accuracy value of the trajectory.

The final step of the research regarding the Monte Carlo simulation will be the evaluation of the simulation results by concrete surveys on the created reference field.

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