Design of an UWB Based Real Time Locating System for Semi-Autonomous Crane Operation

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Abstract –

This paper proposes a localization-based interface for semi-automated crane movement, allowing the crane to navigate to the operator's position via a low-cost Ultra-Wideband (UWB) tag. This could reduce the cognitive load induced by traditional interfaces and improve safety and productivity. Due to the hardware-specific challenges to access Channel Impulse Response (CIR) data in low-cost modules, various mitigation strategies for Non-Line-of-Sight (NLOS) conditions were evaluated. This study examines the exact scenario and implications for anchor placements with a simulated approach and then real-world measurements to examine localization methods. A robotic total station provided the ground truth for tracking the end-effector of a truck-mounted concrete pump as a proxy for crane operations. The evaluation of different localization algorithms, including Non-linear Least Squares, Least Median of Squares, residual based weighting and an RSSI-weighted approach demonstrates that integrating temporal consistency and RSSI values significantly improves robustness against NLOS outliers at a low computational cost. Vertical accuracy was limited by a poor Vertical Dilution of Precision (VDOP) during testing, due to coplanar anchor arrangements. However horizontal positioning remained stable. The findings suggest that the proposed system proves its viability for enhancing the intuitive operation of compact construction machinery in complex environments, but situations where the majority of anchors experience NLOS need to be avoided with proper anchor placements.

Keywords –

UWB; Localization; RTLS; Crane; Interface; Automation; Robotics

1 Introduction

Cranes are essential part of the construction industry. While large tower cranes are typically operated by trained specialists, compact trailer cranes are often used on smaller construction sites where personnel may lack specific training or routine experience. The high proportion of rental machines, frequent operator changes and short operating times mean that routine handling of these cranes is not commonplace. The assignment of functions, i.e., who is responsible for load attachment, crane operation, and unloading, is usually not clearly regulated in everyday work on the construction site. To address this, we propose a localization-based interface to automate crane movement. By utilizing localization technology, the crane can semi-automatically navigate to the operator's current position with minimal manual intervention. In this concept, personnel handling the load are equipped with a low-cost control device containing a UWB (ultra-wideband) tag. This allows the crane to track and follow the user, effectively automating the most aspects of safe operation without requiring advanced operator skills.

Figure 1. proposed concept for location based, shared control of the trailer crane

Since 2024 regulation in the EU has been adapted to allow fixed outdoor usage of UWB devices, enabling new, innovative uses of UWB technology going forward [1]. UWB has proven to be a promising localization technology for multiple applications compared to different, established technologies. It is cheaper than RTK-GNSS solutions providing centimetre-level accuracy, particularly for use cases involving multiple devices. It is also very energy efficient and provides robust ranging in situations which heavily affect different technologies [2]. Optical solutions are also hard to implement for this cause, due to their inherent dependency on lighting conditions and the requirement for an unobstructed line of sight.

2 Related Work and Industry Applications

2.1 Intuitive Crane HMI Concepts

A variety of concepts for novel interfaces and functions that reduce the cognitive load of traditional crane controls for efficient movement already exist. Major manufacturers such as Liebherr already offer different alternative control modes for their tower cranes [3, 4]. Their Positioning Pilot allows operators to record routes which the crane can then repeat semi-automatically. The crane can also store and access different recurring end effector positions semi-automatically. The Guided Hook System for Liebherr cranes allows the person handling load attachment to control a smaller range of movements simply by tilting and turning the hook, without the need for an additional handheld device. In addition to well-established industrial solutions, there are different approaches to achieve more direct, intuitive crane control. Top [5] examines multiple user-centered control schemes in his research, including a direction-oriented approach that tracks the current orientations of the user relative to the crane and transforms the user-centered inputs into crane centered ones. Another approach from his work is a goal-oriented input system, where the user guides the crane by positioning a light point that the crane then follows. Tu et al. [6] follow a similar goal-oriented approach, but the positioning of the goal marker is done in a mixed reality environment.

2.2 UWB locating research

Currently the main industrial application for UWB is indoor localization, following a growing demand for location tracking in GNSS denied environments for logistics and robotics. But the mentioned benefits make it a promising candidate for real time outdoor localization systems, especially in GNSS denied environments or as a low-cost alternative. While the construction environment is usually outdoors, many challenges of indoor locating system still apply. In construction environments, NLOS conditions are primarily induced by structural elements (e.g., reinforced concrete, steel scaffolds, roofing materials) and machinery, necessitating robust mitigation strategies such as those surveyed by Khodjaev et al. [7]. Besides mitigation methods purely based on UWB hardware, sensor fusion approaches can also be found, where for example IMUs are used to allow for more precise UWB localization under NLOS conditions [8].

3 UWB Locating Principle and Mathematical Model

3.1 UWB Hardware

Off the shelf UWB modules from Makerfabs, based on the popular Qorvo DW3000 UWB chip were chosen for testing. These modules allow easy setup of a two-way ranging protocol with up to the eight closest active anchors. The firmware of the modules abstracts the underlying MAC-layer, preventing modifications to the ranging protocol and access to the channel impulse response (CIR). The CIR is the unique signature of a wireless communication channel, displaying the effects of multipath propagation. Reflections cause multiple versions of the signal to arrive at the receiving node and evaluating the attenuations and temporal delay provides additional information about the channel. In addition to the estimated distance, the received signal strength indicator (RSSI) of the signal is provided by the modules. The CIR contains more information than a single RSSI value for NLOS identification which could improve accuracy under severe NLOS conditions. On the other hand, the larger amount of data contained in the CIR means it usually can't be accessed in real-time from low cost UWB Nodes due to limitations of the serial interfaces and processing the signal also requires significantly more resources.

3.2 Ranging Accuracy in LOS and NLOS conditions

The major challenge for all UWB-Locating Systems is dealing with ranging errors due to non-line-of-sight (NLOS) conditions. When there is no unobstructed line of sight between the anchor and tag at the true distance d_{true}, various effects introduce errors in the time-of-flight measurements between the two nodes. Refraction or propagation through obstacles introduces a positive bias b_{NLOS} to the measured distance $\hat{d}$, which is also affected by gaussian measurement noise n.

$$\hat{d} = d_{true} + b_{NLOS} + n \tag{1}$$

The magnitude of this propagation delay depends on the thickness and relative permittivity of the obstacle [9]. If the obstacle weakens the signal from the direct path too much, the leading-edge algorithm, which is responsible for identifying the direct path signal received from noise and multipath signals, may detect a stronger signal from an indirect path as the leading edge. This introduces a positive bias to the distance measurement. While a single, poor measurement might not greatly affect positioning and can be mitigated relatively easily, situations involving NLOS measurements from multiple anchors prove to be a bigger challenge.

During the preliminary measurements two different NLOS scenarios, depending on the permittivity of the obstacle and geometry of the surroundings could be observed: Barral et al. [10] describes them as soft NLOS and hard NLOS. Soft NLOS describes scenarios where there is an obstruction to the direct LOS, but the main signal is able to penetrate the obstacle with enough strength to be identified be the receiver. During hard NLOS, on the other hand, the signal cannot reach the receiver with sufficient RSS via the direct path. Consequently, another indirect path is intercepted and misidentified as the direct path by the receiver. In extreme cases, especially outdoors with long distances the signal might not be picked up by the receiver at all, resulting in complete signal loss. While it is impossible to conclude how the signal exactly propagates in complex environments, the different scenarios provide distinct characteristics. During floor level measurements many of the tested obstacles probably represent soft NLOS. For example, measuring the distance first through an open metal gate and then through the closed gate without moving the tag or anchor resulted in an error of about 2.0 m, while not showing any effect on the signal strength indicator, as shown in Figure 2. Sometimes these NLOS measurements even display better signal strength than the LOS situation, meaning the RSSI alone can't be used as a reliable indicator for NLOS when using these modules. Presumably this value is not an indicator for the first path power, but there is no information provided on how the RSSI value is calculated by the manufacturer. The gaussian noise present in all measurements also stayed similar when NLOS was prevalent.

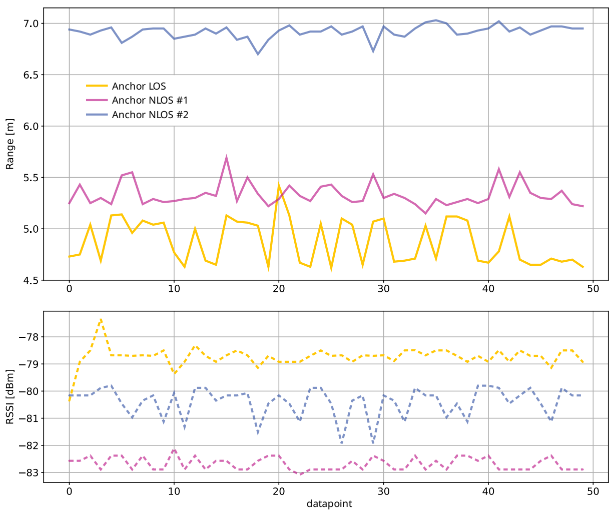

Figure 2. Measured ranges and signal strengths with 5m ground truth through different mediums

Another measurement outside was conducted with the tag attached to a crane-hook and multiple anchors on the ground. The crane hook was the moved above a building. Depending on the position of the anchor-node different effects could be observed. The anchor closest to the building experienced total signal loss. The next anchor didn't experience signal loss right away as the tag was moved further across the roof, but the distance measurement for that anchor, showed discontinuities with very strong outliers. These most likely represent reflected multipath signals from neighboring buildings being wrongfully detected.

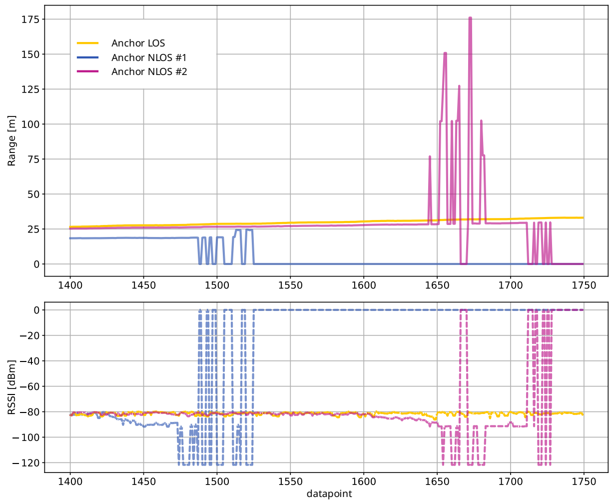

Figure 3. Measured ranges and signal strengths with ground level anchors and tag above the roof

This could also be observed when the either the anchor or tag were placed in a position corresponding with the antenna nulls of either the anchor or the tag. Monopole antennas, like the ceramic ones used in the Makerfabs modules, have an omnidirectional radiation pattern in the horizontal plane, but suffer from inherent gain reductions in the other two planes. This means that the orientations of tag and anchors are also relevant to the system's overall accuracy, or larger antennas with a more even gain distribution have to be used.

3.3 Localization Algorithms

To benefit from the high temporal resolution that UWB offers time of flight (TOF)-based ranging is usually used for locating systems. With TOF-based distances and the known positions of the anchor nodes the position of the tag node can be estimated with various methods. Localization based entirely on distance measurements is referred to as multilateration. Least squares location estimation and particle filters are among the most common techniques described for UWB real time locating systems based on multilateration. In order to make the locating system viable as an input device for cranes, even with multiple NLOS anchors, the biased measurements from these need to be mitigated. Since the hardware that is used does not allow access to the CIR, identifying NLOS conditions is limited to RSSI-based features and temporal consistency checks. Mitigation techniques, such as statistical methods on the other hand only require range measurements. However, these can be improved by providing additional information and weighting the measurements based on this information. Machine learning approaches for NLOS identification and fingerprinting solutions could not be easily applied due to the hardware limitations and the need for a system that works in frequently changing environments and configurations. Instead, a statistics-based approach was chosen. These methods work with all UWB hardware, capable of ranging in a variety of different setups, as long as the exact position of the anchors can be determined.

3.3.1 Non-linear Least Squares Multilateration

For N anchors with known coordinates a_i and the measured distance values d_i,the residual r_i is defined as:

$$r_i(p) = ||p - a_i||_2 - d_i \tag{1}$$

The objective of the algorithm is to find a position p that minimizes the global cost function:

$$\min_p \sum_{i=1}^{N} w_i \cdot \rho_\delta\,(r_i(p)) \tag{2}$$

For this, an initial guess of the position is required for the algorithm. A random initial estimate was utilized for the evaluation of real-time applications, and subsequently the previously estimated position could be utilized. This way the positioning never got stuck in local minimums. To reduce the dominance of single outliers of the regular least square optimization, a robust loss function, like the Huber loss function ρ_δ (4) is used:

$$\rho_\delta(r) = \begin{cases} \frac{1}{2}r^2, & |r| \le \delta \\ \delta(|r| - \frac{1}{2}\delta), & |r| > \delta \end{cases} \tag{3}$$

The threshold δ where the loss transitions from quadratic to linear can be tuned to the expected measurement noise. This way the benefits of squared loss for small residuals and linear loss for larger outliers are combined. The weight factor $w_i$can be used to improve the optimization with different weighting algorithms, like residual based weighting [11].

3.3.2 Least Median of Squares

Another approach to dealing with severe NLOS conditions is optimizing the least median of squares.

$$\min_p med_i(r_i^{\,2}(p)) \tag{4}$$

This method will result a smaller subset of measurements being used than the least squares approach, meaning it has a higher breakdown point than least squares at 50%. At the same time, it is more susceptible to converge in local minima than the least squares approach. To avoid this, a simple multilateration step is required before initializing the positioning system. The previously estimated position can then be used for continuous position tracking. While the Least median of the Squares is more resilient to a high percentage of outliers, it is also less efficient, resulting in longer computation times on less performant hardware.

3.4 Construction scenario simulation

A simple simulation in Unity 3D was used to evaluate anchor placement and test the effects of a variable measurement space with movable anchors on the crane. The NLOS error was simplified by checking the thickness of the obstacle in the direct path between anchor and tag. This only applies the bias of propagation through obstacles and errors due to multipath effects are not simulated. While this does not nearly represent the complex multipath behavior of the measurements observed prior, adding an arbitrary error to NLOS measurements and gaussian noise provided a similar challenge that a positioning algorithm faces with real UWB nodes. The simulation environment enables rapid tests of anchor configurations and avoids the time-intensive manual surveying of anchor coordinates required in physical deployments. To test the effectiveness of various localization methods the tag was moved across a simplified house with a gabled roof, typical for roofing jobs where this kind of trailer crane is usually used.

3.4.1 Anchor placement

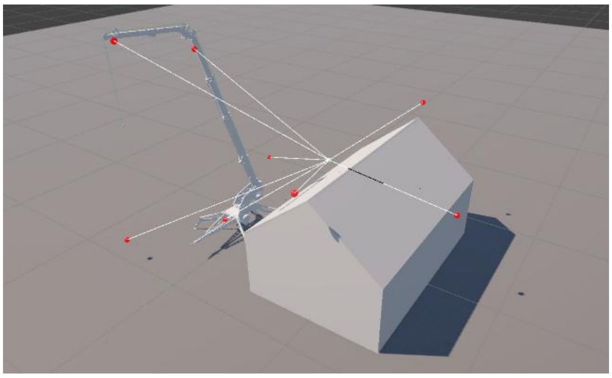

Figure 4. Screenshot of the Unity simulation with the proposed anchor setup for eight anchors

Since the positions of all anchors have to be measured precisely, they should be placed in static positions to maintain a consistent reference frame throughout the construction phase. Ideal mounting positions are on scaffolding with clamps for the roof. For placements on the ground floor, heavy-duty tripods are proposed. To provide best setup with as few anchors as possible they need to be spaced out evenly around the area of operation. Three anchors were placed on the crane itself. One on the trailer at ground level, one on the main boom and one at the end of the jib. The exact position of those anchors is determined by measuring the position and orientation of the trailer itself and forward kinematics. Gabled roofs turned out to present the biggest challenge for anchor placements. In scenarios where the target is on the opposite slope of the crane the gable can lead to NLOS errors for the majority of anchors. The best setup to ensure enough LOS anchors at all relevant positions while maintaining enough spatial diversity in anchor placement to minimize the geometric dilution of position problem is shown in Figure 4.

4 Validation and Results in a dense real-world environment

4.1 Methodology

For this experiment the position of the end-effector of a truck mounted concrete pump was tracked with a robotic total station. The UWB tag was mounted close to the reflector on the TCP, so that the measured position from the total station could be used as a ground truth to compare the UWB positioning against. Seven anchor nodes were placed around the area, mostly on tripods with smaller variations in height. One anchor-node could be placed elevated on scaffolding, to increase the vertical diversity for 3D multilateration. The positions of the anchors were measured with a GNSS rover system. The registration error between GNSS and total station coordinates was minimized using four reference points, resulting in an estimated anchor position uncertainty of ± 5.0 cm.

Figure 5. Positions of the anchors and the tag around the concrete pump used in the experiment

The end-effector of the concrete pump was moved both horizontally and vertically around the area. In total three trajectories were tracked by both the total station and the UWB system. During one measurement one of the seven anchors ran out of battery and the pose of the jib caused severe NLOS for at least three of the six remaining anchors. This meant that the breakdown point of the statistical NLOS mitigation methods was reached and without access to the CIR, there was no way of determining which distance measurements were trustworthy and which were not. During the other measurements the full set of seven anchors was available and the hard NLOS conditions only affected a minority of anchors, why the decision was made to evaluate the performance of the algorithms separately for both cases.

4.2 Results

First the real-time performance of the different localization algorithms was evaluated, directly using the unfiltered noisy range and RSSI values to estimate positions in real-time. The four selected positioning algorithms were the robust least squares method, the same method with additional weights based on distance, consistency of the distance measurements and RSSI values, an iterative, residual based weighting algorithm and the least median of squares calculation. To mitigate single outliers and the position jitter caused by noise, a linear Kalman Filter was applied to the estimated position. From the measurement depicted in Figures 6 and 7, it is apparent that none of the methods evaluated outperforms the others consistently.

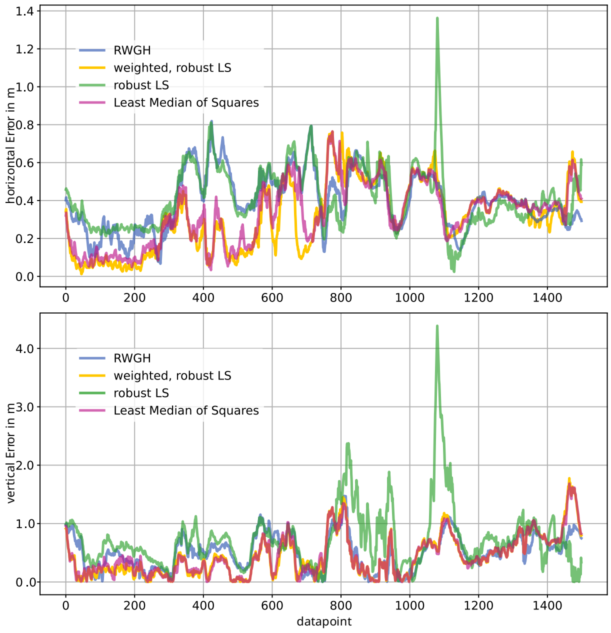

Figure 6. Excerpt of horizontal and vertical positioning errors over a continuous dynamic trajectory

To evaluate the system's effectiveness, the positional error was calculated separately for the 2D horizontal plane and the full 3D position. Across all trajectories, the horizontal accuracy significantly outperformed the vertical accuracy. This discrepancy is attributed to the poor vertical dilution of precision (VDOP), which resulted from the nearly coplanar arrangement of the anchors, necessitated by the site's topography, which limited the potential for significant vertical displacement between the anchor nodes.

From the distribution of errors shown in Figure 8 it is evident, that the additional weighting based on RSSI information and temporal consistency is more effective at mitigating NLOS outliers than the other methods, based entirely on residuals from the range measurements. During the degraded state of the positioning system, shown in Figure 8, the magnitude of positioning errors was significantly higher. Still the additional weighting based on RSSI and consistency of the measurements helped to improve the positioning at a lower computational cost than the residual-based weighting or the least median of squares method. Also, the additional weighting, both by additional factors or iterative and the least median of squares method, is more resilient to large outliers, even beyond the theoretical breakdown point. During this state the accuracy of the positioning is also very dependent on the magnitude of the NLOS ranging errors. In the case that there are not enough LOS or soft NLOS anchors to perform multilateration the positioning result is not salvageable and the user needs to be informed about unreliable positioning and required to manually control the crane.

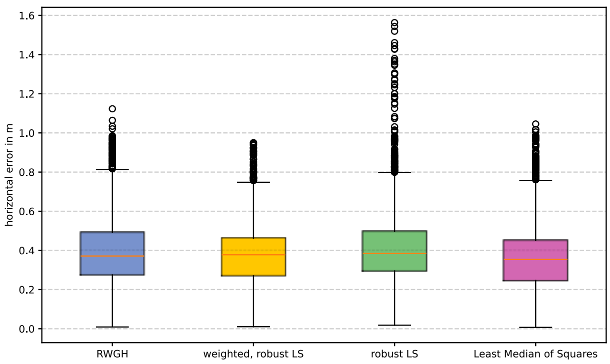

Figure 7. Distribution of horizontal positioning errors during nominal operation

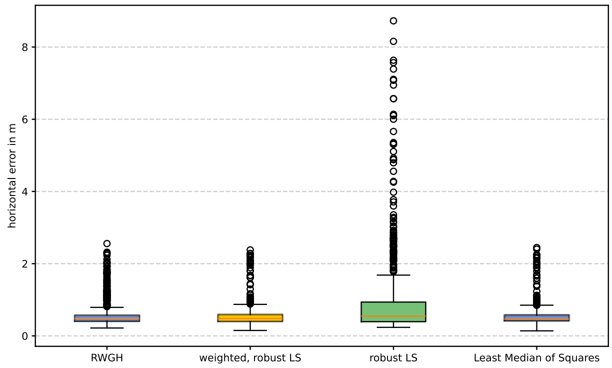

Figure 8. Distribution of horizontal positioning errors during the degraded state

4.3 Discussion and Conclusion

The described experiment proved to be a challenging scenario for the localization algorithms. The boom on which the tag was placed introduced NLOS to multiple anchors on the opposite side of the boom. While hard NLOS conditions and signal loss are pretty easy to spot in the ranging data, it is difficult to evaluate which anchor experienced soft NLOS in which condition because the conditions resulted from the dynamic operation of the machine, rather than a controlled experimental design. At the same time the vertical resolution of the anchor placement was insufficient for reliable vertical localization, due to the limited anchor placement options at the test site. With a difference in anchor height of less than 5.0 m, and only one anchor significantly elevated while the others were within 1.5 m vertically, the poor vertical accuracy can be explained. The proposed anchor setup for crane operation features significantly more diverse options for anchor placement, so the vertical error will be comparable to the horizontal error from the experiment. Even when the system was degraded beyond the breakdown point, the preferred weighted localization still remained within reasonable proximity to the target position. This would allow the UWB guided crane to approach the target and improve the measurements by increasing the proximity of the crane mounted anchors. Overall, we believe that the proposed setup from 3.4.1 should allow for more accurate localization in this specific use case. The crane mounted anchors would be mounted facing down, minimizing the risk for self-shadowing from the machine and providing good vertical spacing for the setup. Potential approaches to lower the breakdown point beyond what is possible with the current hardware are sensor fusion or CIR based NLOS identification, as outlined in 2.2. However, at this point both approaches could not be evaluated for the construction site scenario yet. Going forward, more factors will need to be evaluated, such as NLOS introduced by the hoisted load or the user carrying the tag device. Further experiments with a handheld tag and more controlled NLOS conditions and a setup on the crane will need to be done to evaluate the concept properly.

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