













A quantitative investigation of accuracy and repeatability for deployment of mobile collaborative robots in high-value manufacturing

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Abstract

Current inspection stations often employ fixed arm robots that allow for accurate repetitive inspection but lack flexibility in adapting to new components or orientations and are used for conventionally fixtured parts in a linear manufacturing approach. Recent advances in mobile robotic platforms with updated sensor technologies have improved localization and path planning capabilities, making them a candidate for bringing inspection processes directly to parts at different points in the manufacturing cycle, potentially helping to maintain schedule. However, mobile platforms introduce additional challenges in positional uncertainty which is higher than fixed systems due to the lack of a fixed calibrated location, posing challenges for position-sensitive inspection applications. The focus of this study is to assess the positional accuracy and repeatability of such mobile manipulator platforms and a KUKA KMR iiwa was selected for this study due to its integration of robot arm and mobile base within a single product. The accuracy and repeatability of the mobile platform were evaluated through a series of tests using a precision laser tracker to evaluate the performance of its integrated feature mapping, the effect of various speeds on positional accuracy, and the efficiency of the omnidirectional wheels for a range of translation orientations. Experimental evaluation revealed that enabling feature mapping substantially improved the KUKA KMR iiwa's performance, with accuracy gains and error reductions exceeding 90%. Repeatability errors were measured to be under 7 mm with mapping activated and around 2.5 mm in practical scenarios, demonstrating that mobile manipulators, incorporating both the manipulator and platform, are a step towards

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flexible manufacturing inspection scenarios and provide a diverse alternative to traditional fixed-base industrial manipulators.

Keywords: collaborative-robotics, mobile platforms, non-destructive testing, flexible manufacturing

1. Introduction

Mobile robotic platforms, particularly for warehouse management, are frequently employed for moving goods between stations. Mobile manipulators combine a mobile platform, with an onboard multi-axis manipulator. Currently, mobile manipulators have not been extensively used in high value manufacturing applications, operating autonomously at full capacity. Several factors have impacted the adoption of mobile manipulators, including the costs associated with their implementation, uncertainties in accuracy and repeatability and challenges of floor surface conditions. Additionally, the shortage of qualified personnel to operate these systems and the necessity for updated safety protocols to handle the systems correctly are also significant factors [1].

While fixed arm robots are widely used for automation of cumbersome and repetitive procedures such as welding, metrology, positioning, assembly and inspection in high volume production lines, they are relatively inflexible when it comes to adapting to new components, different component orientations, or new operations [2]. As a result, the environments in which they operate tend to be designed to accommodate the robot's limitations. This is why some businesses opt for manual labor methods instead, especially when dealing with high-mix and low-volume production components [3]. Additionally, reach limitations require installations of additional external axis to introduce more DoF (degrees of freedom) and machining of appropriate gantries or fixtures to handle the components. For instance, aerospace components are often large (>3 m) and necessitate customized systems for manufacturing processes [4] where such systems lack the adaptability and flexibility introducing delays in manufacturing and impacts on production throughput.

To enhance automation uptake, new methods and processes must be designed to be able to adapt to all aspects of the manufacturing operations and the introduction of collaborative mobile robotic platforms is one possible solution. Utilizing modern sensor technologies and algorithms, mobile robotic platforms have shown increased ability and accuracy in localization and path planning making them a candidate for bringing inspection processes to the part. Mobile systems introduce greater flexibility and independence from infrastructures, such as gantry-based systems, decreasing the amount of capital equipment required to accommodate components and potentially allowing for reductions of factory space footprint.

The target manufacturing process of this study is non-destructive testing (NDT) which is a non-intrusive method used to evaluate the properties of materials, components, or systems. NDT techniques include radiographic testing, ultrasonic testing, electromagnetic testing and visual surface

inspection [5] and are a regulatory requirement for the quality inspection of aerospace components prior to certification for flight service operations. By using NDT, defects and irregularities can be detected early on, helping to prevent accidents and costly failures. Due to the need for precise and reliable results in these procedures, an in-depth analysis of mobile manipulator capabilities is warranted, accompanied by the establishment of attributes that define their performance.

By implementing a mobile manipulator solution, the manufacturing process can be streamlined significantly [6]. A mobile solution that can work with a range of sensors and tools, with the ability to travel to different sections of the production line on a factory floor, means there is no longer any need to have several divided areas of a factory, when the process can come to the part. This can therefore reduce the factory footprint significantly, introducing reductions in costs for overheads and equipment. Mobile manipulators can contribute throughout the entire lifecycle of manufactured goods, from production to disposal. They are also capable of working in hazardous environments [7].

Industry 4.0 is synonymous with smart manufacturing and has brought about the necessity for the digital revolution in this sector. This entails the use of artificial intelligence, big data analysis, and other advanced technologies to create interconnected systems that operate more efficiently, autonomously, and effectively [8]. Growing demands and skilled labor shortages have also contributed towards the growing trends of automation across various industries [9, 10]. Manufacturing sectors, in particular, having the highest potential for automation [11]. While automation improves job efficiency and has economic benefits, not all tasks can be automated, creating a need for hybrid work environments combining manual labor with automation [11]. Mobile manipulators are seen as a flexible solution to bridge this gap, as they can navigate and adapt to different environments and tasks effectively.

At present, the International Organization for Standardization (ISO) standard ISO 24647 sets out the criteria for robotic ultrasonic testing, but it does not include mobile manipulators [12]. ISO standard ISO 9283 establishes standardized testing methods for accuracy and repeatability in industrial manipulators [13]. Yet, there is no existing standard for mobile manipulator platforms in terms of repeatability, accuracy procedures, or the specific needs for NDT applications.

Therefore, the aim of this work is to complete a set of tests that will help determine whether the mobile manipulators can achieve the necessary precision required for NDT inspections. This work looks to address this gap by evaluating mobile manipulators in a measurement science context, emphasizing the importance of establishing quantifiable performance

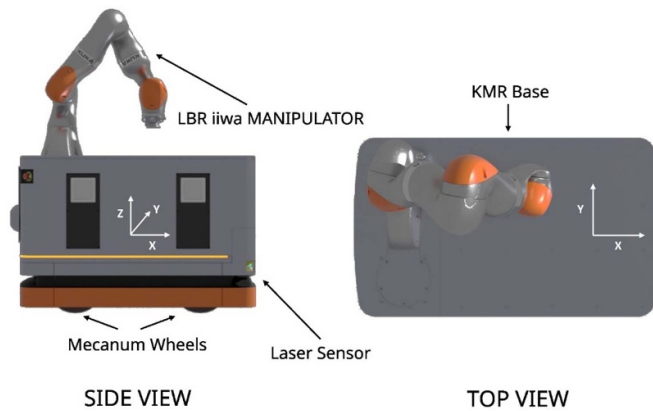


Figure 1. KUKA KMR iiwa mobile manipulator (the coordinate frame refers to the KUKA KMR base frame).

benchmarks such as repeatability and positional accuracy. There are several popular mobile platforms that were considered such as the RB-KAIROS+ and ER-FLEX [13, 14]. These platforms have a range of features such as built in vision systems and integrated Universal Robot arms onboard [15]. The KUKA KMR iiwa [16] was selected for these experiments, due to its robust build, integrated laser sensors, omnidirectional Mecanum wheels, and the scalability of KUKA with its variety of robot systems available—shown in figure 1. The scalability within the KUKA product range presents the opportunity for the lab-environment developments to be transferred to larger industrial robots.

Depending on the purpose and context, NDT can be approached in various ways. In the oil and gas industry, asset monitoring solutions often utilize crawlers and drones to improve flexibility and accelerate the inspection process [17, 18]. Crawlers with ferromagnetic wheels are preferred in situations where the materials are ferrous. In the case of composite materials, often seen in aerospace, automotive, and energy sectors, the current methods are to inspect the parts in a fixed gantry, using a UT water jet or UT immersion scanning with robots [19]. These systems can achieve very precise and repeatable measurements if set up correctly. Robotic manipulators are currently sufficiently accurate for many high value manufacturing applications, as some manufacturers claim repeatability values of ± 0.1 mm [20].

The KMR platform has been studied for multiple applications due to its collaborative nature. Making use of its mapping features and the manipulator onboard the robot, the KMR could open and traverse through doors [21] and the simultaneous localization and mapping approach, SLAM, along with Adaptive Monte Carlo Localization (AMCL), allowed the KMR to create a map of its environment and accurately locate itself within it. The AMCL algorithm uses particles to represent the robot's possible configurations and adjusts their weights based on sensor data to converge towards the actual position. To improve accuracy, additional laser scans are taken in front of the door and the robot aligns itself with the door to transform its frame relative to the door's frame. This strategy of re-aligning after an initial movement can be applied to high value manufacturing for accurate platform positioning.

The accuracy of the inspection process relies on precise positioning and scanning to identify defects accurately. The performance of the mobile platforms can vary, depending on the environment and surface conditions. A vision system has been suggested as a solution to address positional uncertainty. It has been identified as the most effective approach for dealing with positional uncertainty [22]. The concluding remarks found that the vision system was able to achieve compensation with a 0.19 mm offset outperforming the likes of fine positioning and lidar feedback as compensation methods for positional inaccuracies.

A dual arm mobile robot was investigated for its ability to navigate a shop floor [23]. Utilizing the SLAM algorithm solely left the robot out of position by 50–100 mm at times. By introducing AR Tags and a vision system, these errors were reduced to 10 mm or less. The concept of achieving a significant reduction in positional errors by more than 80% through the implementation of an integrated vision system has proven to yield substantial improvement for both existing and for possible future mobile systems.

Several researchers have investigated the validation of the positional accuracy for different platforms. One research team proposed the use of an L-shaped approach to validate the accuracy of their mobile platform [24]. This was found to be too tailored to meet the specific expectations of the use case, without any translation to the KMR iiwa platform testing or quantification. Other groups have looked at testing their robots with circular paths and figures of eight [25, 26]. The results were determined by finding the displacement of the robot after these movements. This work aimed to adopt the suggestion of examining the overall displacement after the paths were completed. However, the paths tested by other researchers appeared unfeasible because of the size difference between the KMR and the robots used for these tests, and effective experimental space limitations [24–26].

The present NDT environments utilizing robotic manipulators are not collaborative in their methods, and still lack the essential technologies to accomplish fully autonomous NDT inspections without human intervention [27].

Currently, there is no research that has presented the use of mobile manipulator platforms for NDT that possess complete autonomy to freely navigate and explore their surroundings. To get baseline values required for a suitable mobile manipulator, the specifications of an in house designed phased array ultrasound roller probe is being utilized [28]. For this roller probe there is a fundamental requirement of a high degree of precision to achieve the expected results. From previous studies, experimental validation has deduced that using such sensors necessitates advanced control capabilities [28, 29]. Optimal detection sensitivity in NDT typically benefits from high precision—such as contact force accuracy of 0.5 N, positional accuracy better than 0.5 mm, and rotational accuracy better than 0.1° —the required defect size can vary by sector. In our case, the industrial partner does not require detection of defects smaller than 9 mm in diameter. The need for such stringent performance metrics further highlights the role of robot metrology in ensuring that robotic systems meet the required tolerances for high-value applications [30]. Programs such as

NIST's Measurement Science for Manufacturing Robotics initiative have also highlighted the critical importance of standardized testing and performance benchmarks to enable greater deployment of autonomous robotic platforms in production environments [31].

The novelty and main contributions of this work are:

1. The development of an experimental procedure, which specifically focuses on testing the precision of mobile robotic platforms.
2. The evaluation of a mobile robotic platform, for the potential use in high-accuracy NDT applications.

The rest of the paper is organized as follows: section 2 describes the experimental setup, section 3 describes the testing procedure. Section 4 provides results and a discussion of the work. Lastly, section 5 concludes the work and discusses future work.

2. Experimental setup

Since there is no standard in place to establish and quantify the capabilities of mobile robots, this paper proposes a new novel strategy, inspired by the ISO 9283 [13], to examine various aspects of the mobile manipulator platforms capabilities. For the KMR that is utilized in this study, this includes:

- a. Assessment of the mapping features,
- b. Understanding the impact of different speeds on the positional accuracy of the KMR,
- c. Testing the operational capabilities of the Mecanum omnidirectional wheels.

The specification for the testing was to ensure that the different aspects and features of the mobile manipulator platforms were tested, including the behavior of omni-directional wheels.

The four mobile platform Mecanum wheels with three DoF enables unrestricted motion and orientation of the platform in two-dimensional space. Strafing movements can occur with the use of Mecanum wheels, in which the robot will move in any direction without changing its orientation. During strafing the platform can complete translations in any direction, without doing a full rotation offering great flexibility in confined environments.

Therefore, given that the KMR can translate to a preset position on the floor either using strafing, or a combination of translation and rotation, one logical comparison point for this Mecanum omnidirectionally enabled platform, is to compare strafing capabilities, figure 2(a), versus full rotations, figure 2(b). The KMR is also capable of driving with solely the encoders fitted onboard, without relying on the laser scanners for laser mapping. For this reason, a plan was devised to test the motions of the KMR during the strafing and rotations using its encoders as compared against the motions with mapping features enabled. This would clarify the benefits of

utilizing spatial localization capabilities. For mobile platforms that lack holonomic capabilities, it is suggested that rotational tests will still yield adequate results concerning accuracy and repeatability capabilities.

The available testing environment was a 3 m by 3 m floor-space, to accommodate the size of the KUKA KMR platform within the temperature controlled laboratory. The floor was an SR1 Floor constructed [32] with epoxy resin, finished with Polyurethane Floor Paint. This means that the surface will not have a variation greater than 3 mm when measured over a distance of 2 m.

The final path design was constructed in the shape of a square with 1 m² in area to test the strafing and rotational capabilities. The path design is demonstrated in figure 2(a), with target positions all spaced 1 m from each other. Moreover, the 4 m square test path provided a uniform distance between all target positions and functioned to ensure that the distance travelled accurately reflected the intended 1 m target for each path. The rotational test followed the same structure as the strafing, shown in figure 2(b).

2.1. Position tracking

A Leica Absolute Laser Tracker AT901 [33] was used to track the performance and movements of the KMR with a 10 μm precision within a 160 m³ volume. Its 3 DoF capability ensured accurate tracking at different heights and angles. In strafing tests, the platform was always facing the same direction, meaning there were no concerns about the laser signal being disrupted, as demonstrated in figure 2(a). However, the manipulator arm onboard interrupted the laser signal when the platform rotated more than 90°, which required a rotation stage to be placed atop of the manipulator, ensuring that its position would always be uninterrupted. This rotation stage was designed to be capable of remaining focused on one point and rotating accordingly in $\pm 2\pi$ to always face a 'true north'. A Vicon T160 camera system [34] with a calibrated absolute error of 0.51 mm [35], was used to determine its true north position and adjust the rotation stage orientation accordingly.

2.1.1. Leica validation. To validate the accuracy of the Leica laser tracker, the reflector was placed in a single position for an hour while the laser tracker recorded every 100 ms. A total of 37 651 entries were recorded, equating to just over 62 min of run time, for validation. This was done to verify the variation in the positional measurements. The results of this initial validation gave further confidence that the Leica could measure to a very high precision degree. The standard deviation was measured at 4.22 μm, 1.89 μm, and 5.21 μm for X, Y and Z components, respectively.

2.2. Controlled features

The integrated SICK S300 laser sensors [36] onboard the KMR platform allowed the robot to localize and navigate. The onboard proprietary KUKA path planning algorithm used a variation of SLAM [37].

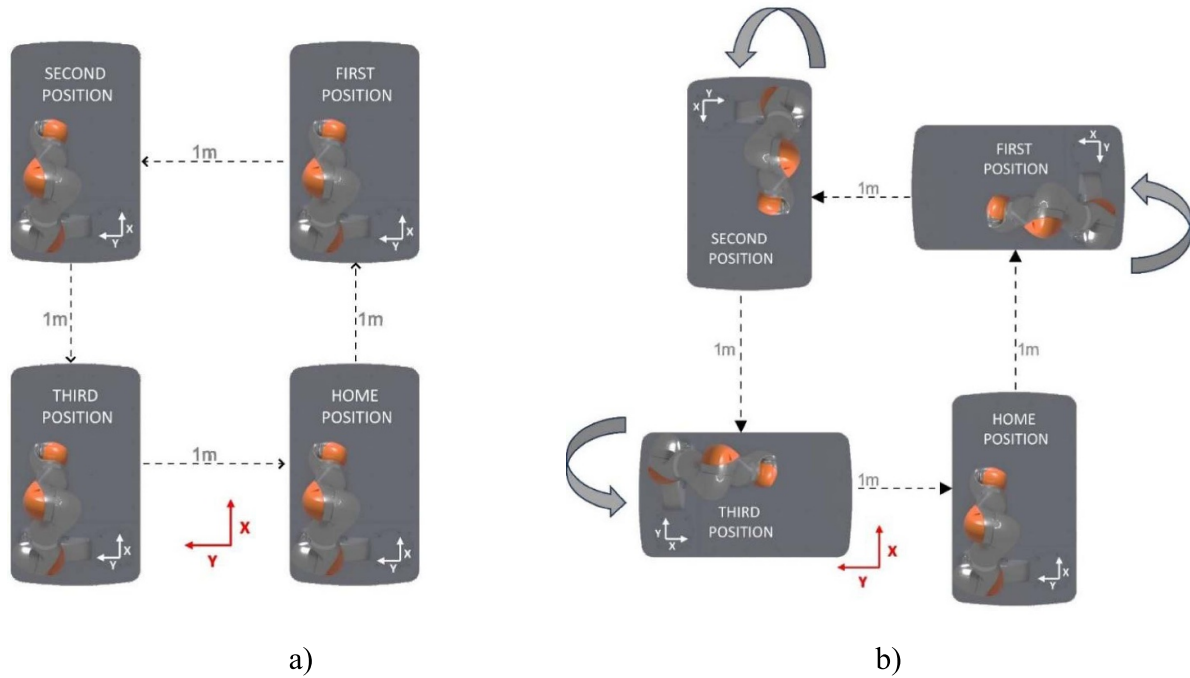


Figure 2. Planned path positions. (a) Strafing, (b) rotational (global frame in red, KMR frame in white).

For laser mapping, there was a need to keep a constant consistent environment, any changes in the layout could impact the mobile manipulator platform’s ability to localize. The SLAM utilization for tracking and mapping in a dynamic environment has been explored previously [38], but its widespread adoption is still pending. This study only focuses on benchmarking the capabilities of the KMR platform, therefore no third-party SLAM algorithms were explored or incorporated into the experiment. The experimental design plan was designed according to ASTM standard F3244-21 for AGV Navigation: Defined Area [39], in which individual tasks are repeated multiple times by the mobile platforms, within a designated floor space outlined by physical barriers. Rigid cardboard boundaries were used to surround the work area providing a non-reflective solid planar barrier framework. The mapped view of the KMR is shown below in figure 3.

The complete working setup as described in this section is presented in figure 4.

2.3. Teaching map and points

The KMR, with its lasers in mapping mode, was manually jogged in an enclosed space to teach the mobile platform the map. To enable the lasers to detect all the features and fluctuations of the surroundings, the KMR was operated slowly in several orientations. The speed, direction, and time spent scanning and re-passing over the surroundings all affected the quality of the map’s representation of the space. Once the mapping method was completed, it was initiated using KUKA’s software package, KUKA Sunrise OS [40], which facilitated communication with the KMR. The map was then loaded onboard the KMR. To verify the robot’s localization, it navigated the surroundings using the loaded map to localize itself. Once

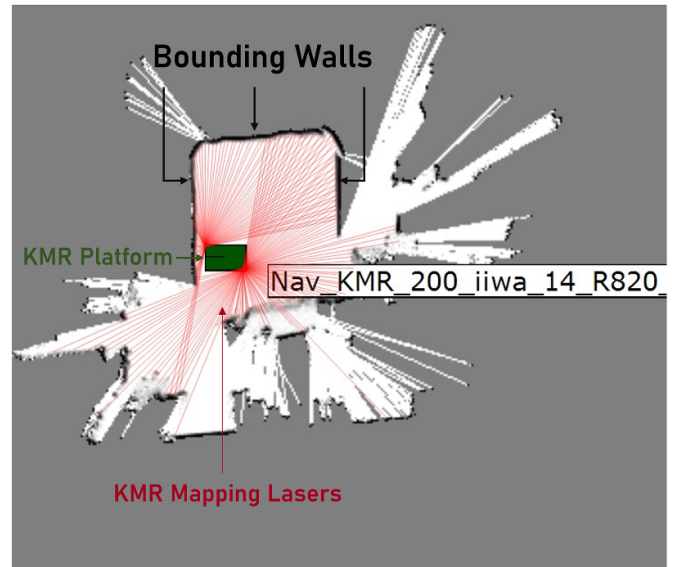


Figure 3. KMR lasers identifying position in SLAM map.

satisfied with its localization, the platform signaled successful positioning in the environment. Using KUKA Sunrise OS features, positions were taught using the platform’s integrated laser sensors to map predetermined locations. The first position taught was the home position. After determining the X and Y values of the home position, each additional position on the map was manually taught with its appropriate offset. The robot then drove to these locations, remapping at each to ensure accurate localization. Both rotational and strafing tests followed this procedure, with the taught positions remaining constant across all tests and speeds.

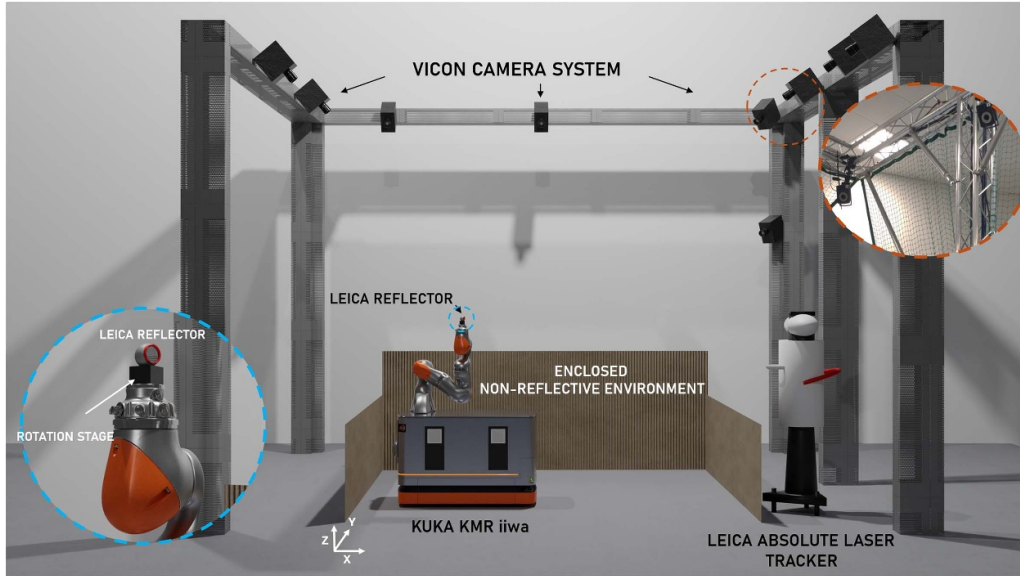


Figure 4. Experimental setup for positional tracking of the KUKA KMR iiwa utilizing Leica laser tracker. (Co-ordinate frame represents the global frame for measurements).

Table 1. Experimental variations with speeds.

Speeds (m s ⁻¹)	Test category			
	Strafing w/encoders	Strafing w/mapping	Rotations w/encoders	Rotations w/mapping
0.08	✓	✓	✓	✓
0.16		✓		✓
0.24		✓		✓

3. Procedure

The testing method consisted of the two previously introduced path options, strafing, and rotations; each variation was tested ten times, with consecutive runs commencing from the previous stop, consistent with ASTM standard F3244-21 [39]. This provided additional information about a final displacement that could be compared to the average displacement between runs. The positional data was obtained from both the KMR and the AT901 tracking system. The ground truth Leica data were compared with the KMR positional data. Of the two path options, four further variations were tested.

- A strafing test using only the encoders,
- A strafing test utilizing the mapping features,
- A rotations test using only the encoders,
- and finally, a rotations test using the mapping features.

Within these four variations, 3 different speeds were tested. Three speeds were chosen to validate if there was any relation to the accuracy and repeatability of the platform with speed. The three speeds chosen for testing were, 0.08 m s⁻¹, 0.16 m s⁻¹ and 0.24 m s⁻¹ as shown in table 1. Odometry only measurements were only needed at the lowest speed to establish a baseline as real inspections would employ the higher

precision of the SLAM navigation with odometry combined with absolute laser mapping.

The speeds of 0.08 m s⁻¹, 0.16 m s⁻¹, and 0.24 m s⁻¹ were selected to evaluate the mobile platform's performance under safe and controlled conditions. The lowest speed, 0.08 m s⁻¹, reflects a realistic operational velocity for *in-situ* inspection tasks, where stability and measurement accuracy are critical. All chosen speeds ensured smooth motion without introducing excessive acceleration or vibration that could cause the platform to shake or reduce the integrity of data capture. Additionally, these speeds were within the tracking capabilities of the onboard laser system, avoiding disruptions or safety-related interruptions due to loss of signal or forced emergency stops.

In the absence of a standard for evaluating the accuracy and repeatability of a mobile platform, a guideline was established with proposed definitions:

- **Repeatability:** The ability of the system to return to its original starting position.
- **Repeatability displacement error:** The distance between the system's returned position and its original starting position.
- **Repeatability displacement accuracy:** The difference between the ground truth position (measured by the absolute tracker) and the position reported by the KMR.

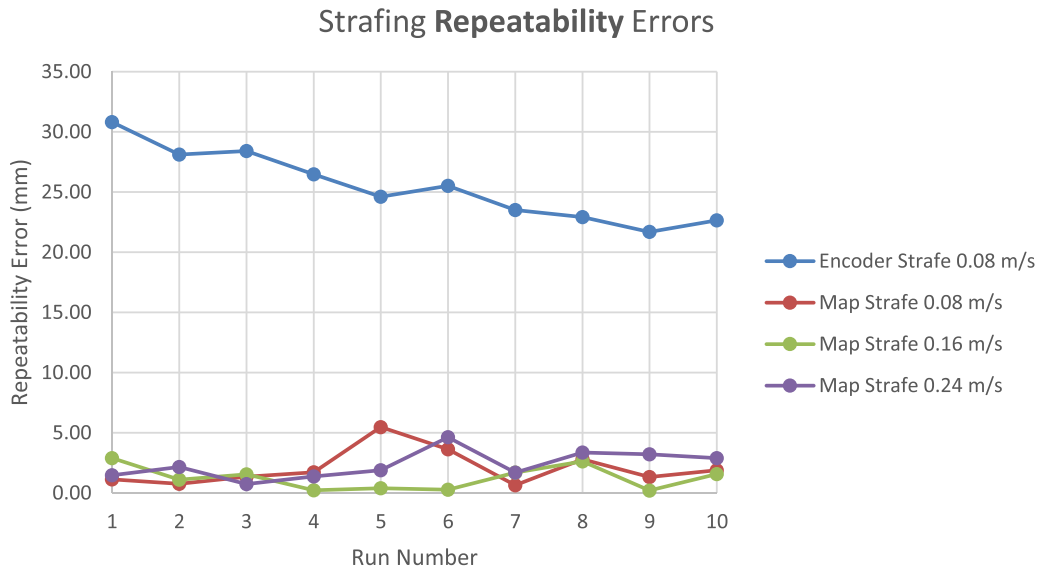


Figure 5. Strafing repeatability errors.

4. Results and discussion

In this section, the findings of the study, are presented. The results are presented in 4 graphs. The first 2 display the repeatability error of the mobile platform, across each of the runs. For the strafing and rotational tests. The second two graphs show the displacement error of the platform, across each of the runs. This allows a more complete result of the platforms performance. The graphical data is also summarized into 4 tables, with the mean and standard deviations of the data.

4.1. Repeatability error

The repeatability errors presented in this section are the difference in values reported between the measured ground truth, from the AT901 tracking system, and the reported value by the KMR platform.

The results from the strafing repeatability tests, presented in figure 5, demonstrate the repeatability errors across each test run. The most notable observation is that the encoder error was consistently larger than the mapping errors by a significant margin. For all test runs, the differences between the mapping and encoder errors remained above 15 mm, highlighting a substantial gap in performance. Furthermore, a trend of decreasing error was observed as the number of runs increased for the encoder tests, suggesting an improvement in the KMR's reporting accuracy over time.

Enabling the mapping features resulted in a noticeable reduction in error, with no mapped run exceeding a 6 mm error in the strafing tests, as shown in figure 5. The errors were more random in nature compared to those observed in the encoder tests, and no evident pattern emerged when mapping was enabled. Additionally, variations in speed had minimal impact on the error results, as reflected by the mean and standard deviation values in table 2.

The largest standard deviation was recorded at 0.08 m s^{-1} (1.43 mm), followed by 0.24 m s^{-1} (1.11 mm) and 0.16 m s^{-1} (0.94 mm). The mean errors also aligned with this pattern, with the 0.16 m s^{-1} test yielding the smallest mean error of 1.26 mm, followed by 0.08 m s^{-1} (2.08 mm) and 0.24 m s^{-1} (2.35 mm). These improvements were substantial, particularly in comparison to the encoder test, which had a mean error of 25.48 mm and a standard deviation of 2.08, representing an improvement of over 90.8% following the activation of mapping features.

The introduction of rotational paths introduced a new layer of complexity, leading to different results. As seen in figure 6, the repeatability errors for the rotational tests showed a less clear trend than those observed in the strafing tests.

Notably, the encoder errors were not the worst performers in this scenario. Shown in table 3, the 0.24 m s^{-1} speed for the mapping test showed a mean error of 6.58 mm, which was larger than the errors for the other mapped tests (1.83 mm and 1.88 mm).

This pattern is consistent with the strafing tests, where speed changes did not have a significant statistical effect. However, the noticeable difference between the 0.24 m s^{-1} test and the lower speeds suggests that the complexity of the path has a threshold beyond which errors increase. In the rotational tests, enabling mapping resulted in a 45.3% reduction in error at the lower speeds but an increase of 90.9% at 0.24 m s^{-1} .

4.2. Displacement error

To gain further insights into the platform's performance, displacement errors were also evaluated. Displacement error was defined as the difference between the current starting position and the initial position at the beginning of each experiment. The reference point remained consistent when comparing different runs, allowing for a direct comparison of displacement performance across test cycles.

Table 2. Tabulated strafing repeatability errors.

Repeatability Error Strafing Tests (mm)				
Runs	Encoder 0.08 m s ⁻¹	Map 0.08 m s ⁻¹	Map 0.16 m s ⁻¹	Map 0.24 m s ⁻¹
1	30.81	1.12	2.90	1.48
2	28.13	0.76	1.10	2.16
3	28.42	1.36	1.56	0.74
4	26.48	1.73	0.23	1.38
5	24.61	5.48	0.39	1.89
6	25.52	3.64	0.26	4.63
7	23.52	0.65	1.68	1.71
8	22.93	2.79	2.63	3.37
9	21.69	1.32	0.21	3.22
10	22.66	1.90	1.58	2.90
Mean	25.48	2.08	1.26	2.35
STD	2.80	1.43	0.94	1.11

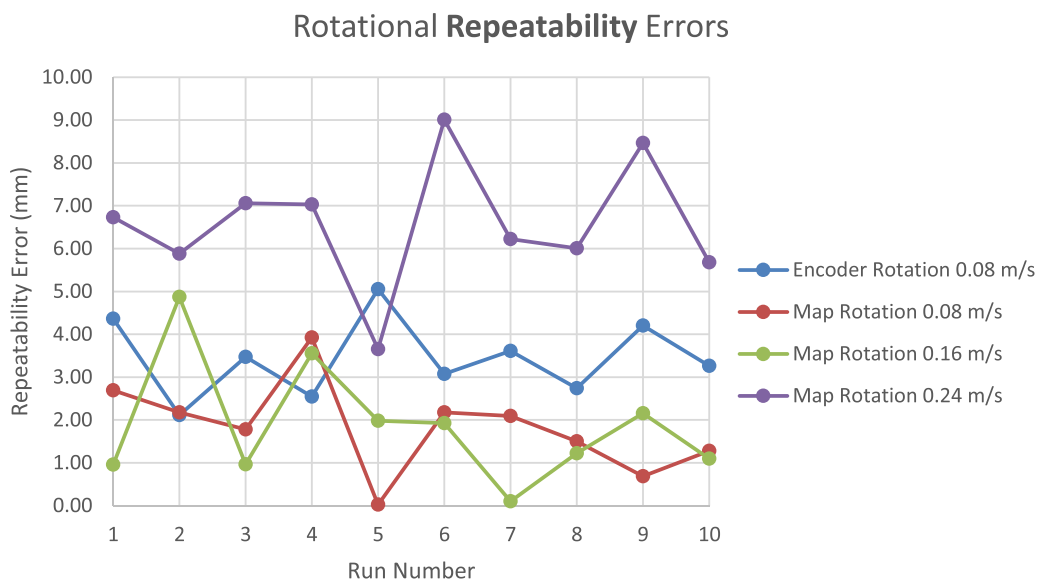


Figure 6. Rotational repeatability errors.

Table 3. Tabulated rotational repeatability errors.

Repeatability Error Rotational Tests (mm)				
Runs	Encoder 0.08 m s ⁻¹	Map 0.08 m s ⁻¹	Map 0.16 m s ⁻¹	Map 0.24 m s ⁻¹
1	4.37	2.70	0.96	6.73
2	2.11	2.18	4.87	5.88
3	3.47	1.78	0.96	7.06
4	2.55	3.93	3.55	7.03
5	5.06	0.02	1.98	3.65
6	3.07	2.18	1.92	9.01
7	3.61	2.09	0.10	6.23
8	2.74	1.50	1.22	6.01
9	4.20	0.69	2.16	8.47
10	3.26	1.28	1.10	5.68
Mean	3.44	1.83	1.88	6.58
STD	0.85	1.02	1.33	1.42

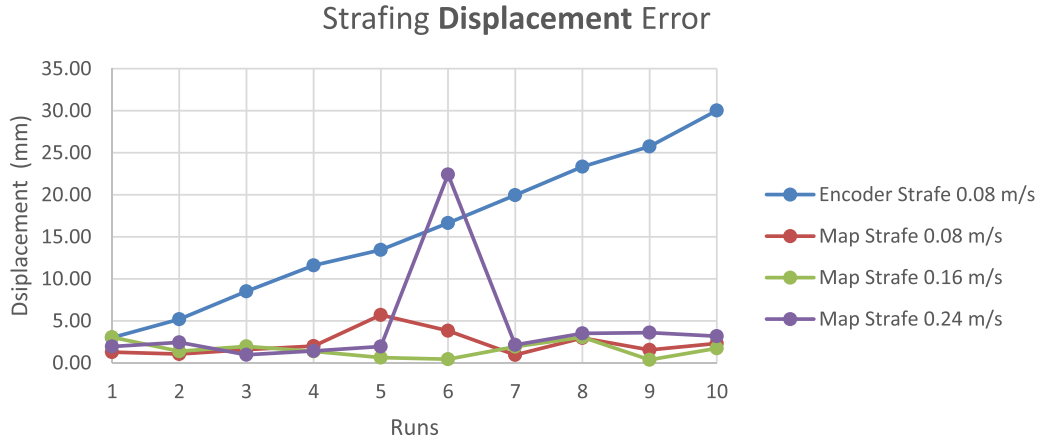


Figure 7. Strafing displacement errors.

Table 4. Tabulated strafing displacement errors.

Displacement error strafing tests (mm)				
Runs	Encoder 0.08 m s ⁻¹	Map 0.08 m s ⁻¹	Map 0.16 m s ⁻¹	Map 0.24 m s ⁻¹
1	3.00	1.28	3.05	1.94
2	5.19	1.05	1.39	2.44
3	8.51	1.57	1.96	0.97
4	11.60	1.99	1.37	1.42
5	13.45	5.70	0.62	1.94
6	16.63	3.82	0.44	22.41
7	19.95	0.95	1.94	2.14
8	23.34	2.96	3.04	3.51
9	25.75	1.54	0.37	3.60
10	30.03	2.32	1.73	3.17
Mean	—	2.32	1.59	4.35
STD	—	1.41	0.91	6.07

In contrast to the downward trend in repeatability error observed in the encoder test in figure 5, the displacement errors showed an upward trend as the runs progressed, as presented in figure 7.

This suggests that while encoder performance improved in terms of error reporting, the platform’s actual position continued to drift off-target over successive runs. With the activation of mapping features, the trends in displacement error were similar to those in the repeatability errors. The 0.16 m s⁻¹ test again demonstrated the best performance, with the smallest mean displacement error (1.59 mm) and standard deviation (0.91 mm), presented in table 4. The 0.08 m s⁻¹ test showed a mean displacement error of 2.32 mm and a standard deviation of 1.41 mm, values that were comparable to those observed in the strafing tests.

However, the 0.24 m s⁻¹ test exhibited an outlier, with a displacement error of 22.41 mm recorded in one run. Interestingly, this outlier was followed by a significantly reduced error of 2.14 mm in the subsequent run. This anomaly may suggest that the KMR did not report its position as accurately during that specific run, although overall reporting improved relative to the encoder-based tests. By the 7th run, the platform was able to return to its target position within a margin of <3 mm, indicating that the system is capable of

recovering from such outliers. Excluding this outlier, the mean displacement error for the 0.24 m s⁻¹ test would have been 2.35 mm, with a standard deviation of 0.86, aligning more closely with the other mapped tests.

Similar trends were observed in the rotational tests, where a nearly linear increase in displacement error was evident for encoder-based tests, shown in figure 8.

The displacement errors for the rotational tests were considerably larger than those observed in the strafing tests. The tabulated results, table 5, showed the initial displacement error for strafing was 3.00 mm, whereas for the rotational tests, it was 17.91 mm. The final displacement errors for strafing and rotational tests were 30.03 mm and 177.31 mm, respectively. Although the repeatability errors for rotational tests remained under 3.5 mm, the displacement errors were significant, suggesting that encoder-based systems may not be suitable for applications requiring high precision, especially in complex movements.

Mapping-enabled tests showed considerable improvement in both repeatability and displacement errors, with the 0.08 m s⁻¹ and 0.16 m s⁻¹ tests yielding mean displacement errors of 1.93 mm and 2.00 mm, respectively. However, for the fastest speed of 0.24 m s⁻¹, the mean displacement error increased to 6.65 mm, with a standard deviation of 1.44 mm.

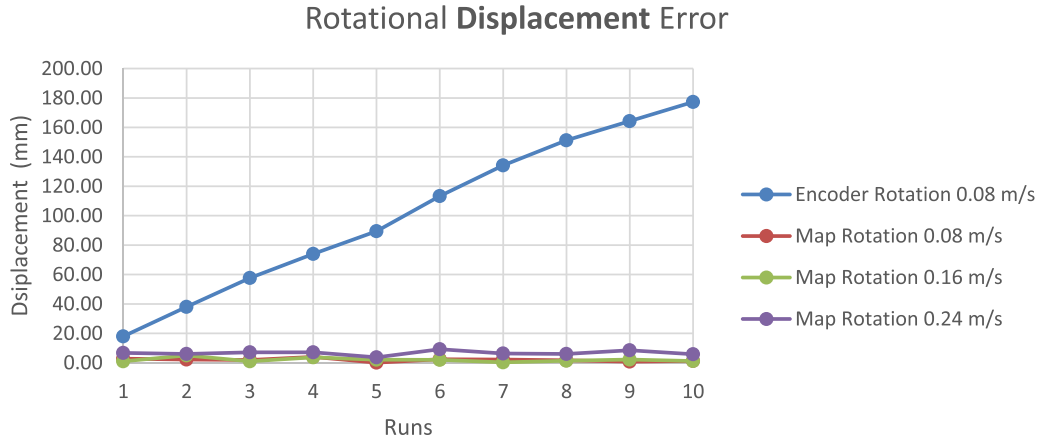


Figure 8. Rotational displacement errors.

Table 5. Tabulated rotational displacement errors.

Displacement error rotational tests (mm)				
Runs	Encoder 0.08 m s ⁻¹	Map 0.08 m s ⁻¹	Map 0.16 m s ⁻¹	Map 0.24 m s ⁻¹
1	17.91	2.79	1.03	6.75
2	38.00	2.24	4.97	5.98
3	57.66	1.87	1.04	7.16
4	73.96	4.02	3.73	7.07
5	89.49	0.07	2.12	3.68
6	113.31	2.37	1.99	9.19
7	134.13	2.23	0.33	6.33
8	151.22	1.68	1.35	6.02
9	164.26	0.77	2.24	8.53
10	177.31	1.31	1.17	5.83
Mean	—	1.93	2.00	6.65
STD	—	1.04	1.33	1.44

For rotational movements, lower speeds (up to 0.16 m s⁻¹) appeared to offer the best performance, yielding repeatability and displacement errors below 2 mm. In contrast, using encoders alone for complex movements, while offering repeatability, resulted in large displacement errors, which would not be acceptable for scenarios demanding high accuracy.

5. Conclusion

The desire to explore greater flexibility in the high-value manufacturing industry by introducing mobile manipulators is a promising opportunity. For a successful introduction of such technologies, procedures and knowledge must be in place to understand the capabilities and limitations of these mobile manipulator platforms.

To address this gap, a novel experimental procedure was presented in this paper to quantify and understand the limitations and capabilities of the KUKA KMR iiwa. This was done by assessing the use of the mapping features, understanding the impact of different speeds on the positional accuracy of the KMR and testing the operational capabilities of the Mecanum omnidirectional wheels.

The KUKA KMR iiwa mobile manipulator is quoted to achieve positioning accuracies of up to ± 5 mm [41]. However, the results of this work demonstrate that the actual accuracy falls short of the stated values. Notably, it appears that the KMR tends to underestimate its error when using its encoders only compared to the AT901 readings. When using mapping features and laser data, the KMR then overestimates its performance.

The results of the strafing and rotational path tests demonstrated that enabling mapping features significantly enhanced the KMR's performance, particularly in terms of repeatability and displacement errors. While encoder-based systems showed consistent repeatability errors, they were prone to increasing displacement errors over successive runs, suggesting that, although reporting accuracy improved, the platform's actual position drifted over time. In contrast, the mapping features substantially reduced both repeatability and displacement errors, with the greatest improvements observed at lower speeds (0.08 m s⁻¹ and 0.16 m s⁻¹).

Mapping's impact on rotational paths was more nuanced. While the 0.24 m s⁻¹ test in rotational movements showed increased displacement errors, the overall trend indicated that lower speeds yielded more accurate performance, with displacement and repeatability errors remaining under 2 mm.

These results highlighted the importance of speed and path complexity in optimizing performance. Encoder-based systems, while capable of repeatable movements, were found to be unsuitable for high-precision applications due to significant displacement errors, especially in more complex rotational movements.

Overall, the integration of mapping features provided a substantial improvement over purely encoder-based systems, marking a significant advancement for applications requiring precise and repeatable positioning—an improvement expected to generalize across other mobile platforms. However, careful consideration of speed and path complexity will be essential to maximize performance, particularly in scenarios demanding high accuracy.

The required accuracy for precise NDT inspections is 0.5 mm, the onboard manipulator, KUKA LBR iiwa, has been previously investigated and proven to have a repeatability of <0.1 mm [16]. While such precision supports high-sensitivity NDT applications, it is important to note that accuracy requirements can vary by industry. In our case, the industrial partner requires detection of defects no smaller than 9 mm in diameter.

With the results presented here, the system could be suitable for certain NDT tasks. However, for NDT applications demanding higher precision, external metrology assistance would likely be necessary. These findings, while focused on NDT due to its strict accuracy demands, highlight the broader applicability of mobile manipulation platforms across manufacturing. The demonstrated precision enables potential deployment in handling tasks, such as those found in pharmaceutical [42] and pick-and-place applications, where less stringent requirements can be offset by sensing systems.

In future studies, we aim to expand upon these findings by evaluating how the integration of additional odometric sensing features and external references could improve the real-time precision necessary for the KMR platform. Subsequent research might entail testing in a larger environment, which could yield slightly varied results and potentially offer findings that are more representative. Additionally, upcoming projects can focus on analyzing and understanding the errors associated with moving to a designated position and then operating the arm, allowing for a more in-depth comprehension of the combined errors in mobile manipulation.

Data availability statement

The data cannot be made publicly available upon publication because they contain commercially sensitive information. The data that support the findings of this study are available upon reasonable request from the authors.












Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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