Ultra-Wideband for Distance Measurement and Positioning in Functional Safety Applications

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***Abstract*—Positioning techniques based on wireless communication systems are nowadays spreading in several diverse fields, such as factory automation, process control, distributed measurement, smart homes, and healthcare. Focusing on factory automation, such techniques may reveal particularly helpful to implement functional safety systems for applications, like mobile robotics, that involve the coexistence, and possibly the collaboration, of robots and human operators. Indeed, an effective localization system may be exploited by safety procedures to avoid harmful contacts between people and mobile equipment. In this paper we address the use of the Ultra–Wide–Band (UWB) technology to achieve positioning data, in such contexts. Specifically, after a short description of UWB, as well as of the typical positioning techniques, we discuss the general features of functional safety systems for mobile robotics, focusing on their common requirements. Then we provide the outcomes of an extensive measurement campaign in which we used UWB commercial components to evaluate the distance between devices as well as the position of mobile nodes. The obtained results are encouraging, since on the one hand they confirm the suitability of the proposed system whereas, on the other hand, they pave the way to future promising developments.**

***Index Terms*—Factory Automation, Ultra-WideBand, IEEE 802.15.4a/z, Localization, Positioning**

I. Introduction

Reliable positioning in both indoor and outdoor environments, plays an important role in many application fields, such as factory automation, measurement, automotive and personal healthcare, to mention some. Particularly, in factory automation systems there are applications such as mobile robotics that may involve the coexistence of mobile equipment and people. In these scenarios, functional safety systems may get significant benefits by distance measurement and positioning, since they allow to design suitable techniques to avoid unwanted and dangerous contacts between robots and human operators.

Traditionally, wireless technologies have been widely employed for such a kind of applications. As a matter of fact, different wireless communication systems have been used over the years to implement several strategies for reliable positioning [1], and this trend is still progressively growing. Indeed, nowadays we are witnessing the rise of a new generation of localization technologies, namely, micro-location-based systems, which are theoretically able to pinpoint locations more accurately than ever before. For example, Bluetooth 5.1 makes available the Angle of Arrival (AoA) technique [2] which, by means of an algorithm and an antenna array, is able to calculate the angle between the plane of a receiving station and that of a transmitting one with a precision as low as 5 degrees. Wi-Fi, to get positioning data, uses the Receive Signal Strength Indicator (RSSI) in combination with other techniques, such as Time of Flight (ToF) or Time of Arrival (ToA), within dedicated RSSI fingerprinting algorithms [3]. The effectiveness of these positioning techniques may be limited by their high computational loads, as they require rather complex measurements and elaborations to achieve good location performance. This also implies that the power consumption related to these technologies is significant, and that often their outcomes may be delayed, possibly resulting in a non satisfactory timeliness.

In this context, the Ultra-Wideband standard, IEEE 802.15.4z [4], represents an appealing opportunity since it can provide performance that may specifically address the needs of real-time capabilities in ranging, positioning and localization applications [5]. Indeed, this new standard guarantees good accuracy, reliability, timeliness and low power-consumption. Actually, UWB can pinpoint people and things within a few centimeters, and presents high immunity to both multipath and interference. Moreover, it is 50 times faster than GPS, with updates up to 1,000 times per second and it is low-powered compared to other mainstream electronic technologies [6], [7]. This paper addresses both distance measurement and positioning performance of a UWB–based system by investigating its accuracy under various environmental conditions in order to assess its suitability for the functional safety of critical applications such as mobile robotics, as will be described in Section IV.

In this detail, the paper is organised as follows. Section II provides some theoretical background about UWB. Section III introduces related works. Section IV describes the targeted applications and the contribution proposes by this paper.. Section V presents the experimental session carried out to characterize the distance measurements for a pair of sensors. Starting from this ranging characterization, Section VI proposes a deterministic 2D triangulation algorithm designed to solve the positioning problem. Finally, section VII concludes the paper.

II. Theoretical Foundations: Ultra-Wideband

According to the Federal Communications Commission (FCC), the UWB radio frequency ranges from 3.1 GHz to 10.6 GHz, with a minimum signal bandwidth of 500 MHz. UWB uses short sequences of very narrow pulses using binary phase-shift keying (BPSK) and/or burst position modulation (BPM) to encode data. The use of narrow pulses results in a transmission exhibiting wide bandwidth, improved range, reduced sensitivity to narrowband interference, and the ability to operate in the presence of multi-path reflections. In particular, the recently released standard, IEEE 802.15.4z, specifically stresses robustness and immunity and ensures a high level of reliability. Moreover the standard was designed to limit power consumption and to support large numbers of connected devices. UWB localization is based on the Time of Flight (ToF) technique [8], which is a method for measuring the distance between two radio transceivers by multiplying the ToF of the signal by the speed of light. From this basic principle, based on the target application's needed, UWB-based localization can be implemented in different ways. In detail, 3 methods are standardized: Two-way ranging (TWR) [9], Time difference of arrival (TDoA) [10], and Phase difference of arrival (PDoA) [11]. The first method, TWR, is the simplest one, since it calculates the distance between one device and another one by determining the ToF through the exchange of timestamped messages, and then multiplying the time by the speed of light. As can be seen in Fig 1, one device initiates communication with another by sending a poll request. The second device responds to this message including the time to elaborate the response (T_{reply}). When this message is received, the first device calculates the time elapsed between the initial message's transmission and the reception of the subsequent response (T_{round}). The Time of Flight (ToF) is easily calculated as:

$$ToF = \frac{T_{round} - T_{reply}}{2}$$

and finally the distance could be easily calculated multiplying for the speed of light.

The second method requires a more complex network configuration with a shared synchronized time information and a relative synchronization algorithm and with fixed, well known, locations for some specific device called anchors [12]. The mobile devices periodically send messages called beacons. When an anchor receives the beacon, it timestamps it, based on the common time. The timestamps from multiple anchors

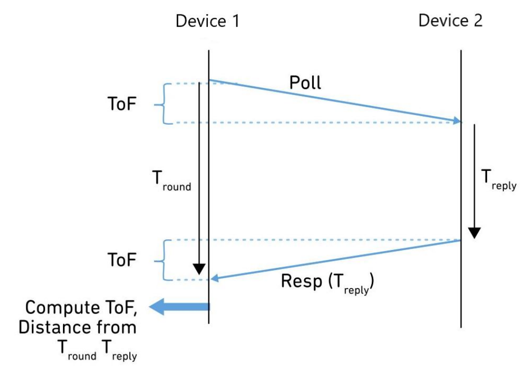

Figure 1. Two Way Ranging Scheme

are then forwarded to a central location engine, which will run multilateration algorithms based on TDoA of the beacon signal at each anchor. The result will be either a 2D or 3D location for the mobile devices.

Finally, the last method, PDoA, combines the distance between two devices with a measure of the bearing (the horizontal angle between the direction of an object and another object) between them. To accomplish this, one of the devices must have at least two antennas and be capable of measuring the phase difference of the arriving signal's carrier at each antenna. This technique is similar to the aforementioned AOA used by Bluetooth, even though UWB employs it in conjunction with the ToF technique.

III. Related works

UWB technology has attracted substantial attention due to the described characteristics. Beside the centralized usage of anchor-based systems [13], also point-to-point ranging started receiving much attention [14]. Possible topologies were analyzed in [15], [16]. In addition, the scalability of UWB-based localization was analyzed in [17] showing the huge impact of the coordination protocol on scalability.

Also the synchronization algorithms has an important impact for the UWB systems, and it was deeply analyzed in [18], [19]. Large scale networks were analyzed in [20] with an anchor-based TDOA strategy. Finaly, also the impact of TWR between all nodes in real-time network was analyzed in [21]. Once obtained the distances between nodes, trilateration [22] and iterative multilateration [23] could be done. In [24] it was used least square optimization to find the coordinate of the nodes by selecting reference nodes to do them. In [16] a model was designed and an extended Kalman filter was used for tracking a drone. Moreover, many other machine learning approaches can be used, as proposed in [25],and in particular deep learning, that has proven its effectiveness in a variety of fields [26], [27].

IV. Targeted Applications and contributions

Distance measurement and positioning represent key issues in several fields of application. In this paper we address functional safety and, in particular, we refer to the mobile robotics field, likely one of the most promising and complex, which typically involves the presence of human operators. In this context, functional safety plays a fundamental role, since it is of prominent importance to avoid the presence of people in the working area of robots during operation [28]. To achieve such a goal, a safety procedure has been designed based on real–time measurement of the distance between robots and human operators as well as on the calculation of the operators position. Particularly, the safety procedure has to stop robots when the distance with human operators becomes lower than a given threshold. Moreover, the safety procedure exploits positioning to assess whether or not human operators are located in specific safety zones.

A UWB system is used to implement distance measurement and positioning. Specifically, some UWB anchors are located on the robots (which actually implement the safety procedure), whereas human operators are equipped with small UWB tags. This allows distance measurements with techniques like those described in the previous section. Positioning is then achieved via an algorithm that elaborates the distances measured by each anchor.

The described scenario has some requirements, mostly derived from the functional safety features, that are different from those traditional tracking and positioning systems. Indeed, on the one hand, it is fundamental to have a sample rate able to guarantee the timely intervention of the safety procedure. Specific reaction times in this respect are strictly related to the application, nonetheless, typical values are in the range of 200–300 ms. On the other hand, requirements on the accuracy of distance measurement and positioning may be relaxed, since safety areas do not need to be delimited with centimeter precision. Finally, for the considered applications it is essential to limit the complexity of the safety procedures, since they are often implemented on low cost devices (for example, in a prototype application we developed, we used an Arm Cortex–M0 processor). In this context, this paper provides a simple deterministic algorithm, which is usable in safety critical system, with small computational resources, for tracking moving targets. In addition, the technique proposed is simply to configure, allowing to invert anchors and distances between them and not requiring a training dataset, as for a machine learning approach.

V. First test set: two nodes distance measurements

In this section, the experimental campaign, aiming at a precise characterization of two commercially available Ultra-Wideband sensors measuring the distance between each other, is presented and results are discussed and compared with those of one possible industrial commercial implementation, such as Terabee Follow-me [29]. Moreover, the obtained results have been analyzed in the light of the application requirements. For these tests we used two modules including Decawave/Qorvo Ultra-Wideband DWM1001c. They have a 6.5 GHz band, with 5 possible channels, all FCC/IEC RF Certified for permanent indoor and outdoor usage. In these tests, the time of flight was calculated using the simplest algorithm (Two-way-ranging) and then the distance was obtained by multiplying the obtained ToF for the speed of light. The tests were carried out to characterized the system in an indoor environment, analyzing the impact of possible obstacles and different distances. The sampling time of the sensors has been set to 25 ms. For every performed test, we acquired the measured distance for a time interval of 25 s, leading to the acquisition of 10000 unique measurements. The first test has been executed with the sensors positioned at a distance of 1.23 meters, inside a room with some other objects, but with no direct obstacles. Results are provided in Fig. 2 and in the first row of Table I, respectively. As can be seen in Fig. 2, measurements are affected by a rather high noise and a quantization step of about 18–19 mm can be detected. Despite that, the measured accuracy is in agreement with the reference technical specification (which indicates 25 cm) and it is definitely suitable for the targeted applications. Moreover, measurements showed a good repeatability, as can be evinced by the low value of the standard deviation.

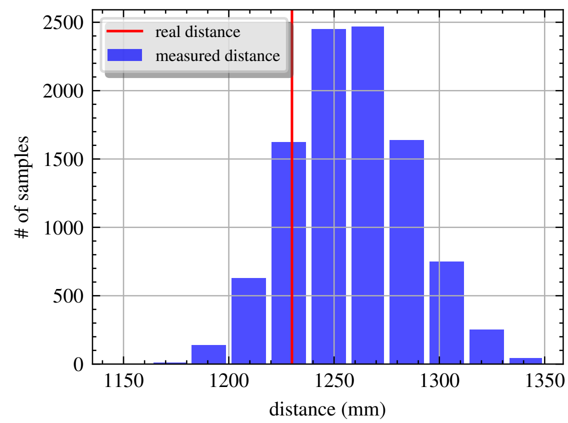

Figure 2. Distances measured Test 1

A second set of test has been performed to evaluate the precision of the measurement at different distances, with the sensors in the same room and with some obstacles. Results are provided in Fig. 3 and Table I, respectively. In particular we are referring to test numbers 2, 3 and 4. In this case, Fig. 3 plots the Probability Density Functions (PDFs) of the distances.

Table I
Experimental results

Test (#)	**Real dist. (m)**	**Mean m. dist. (m)**	**Std. Dev. (m)**	**Mean Err (m)**	**Max Err (m)**	**Obst.** (s/m)	**Diff. rooms** (bool)
1	1.23	1.248	0.028	0.018	0.120	NO	NO
2	4.1	4.387	0.031	0.287	0.421	some	NO
3	9.21	9.394	0.025	0.184	0.283	some	NO
4	2.18	2.323	0.029	0.143	0.334	many	NO
5	8.07	8.636	0.110	0.566	1.329	many	YES

As can be seen, in some cases, particularly for tests number 2 and 4, the mean measured distance is affected by a non negligible bias error (about 7% and 6.5%, respectively). This is most likely due to the presence of objects between the sensors which did not allow a direct path to the signal. However, even if this is an unwanted condition, the overestimation can be

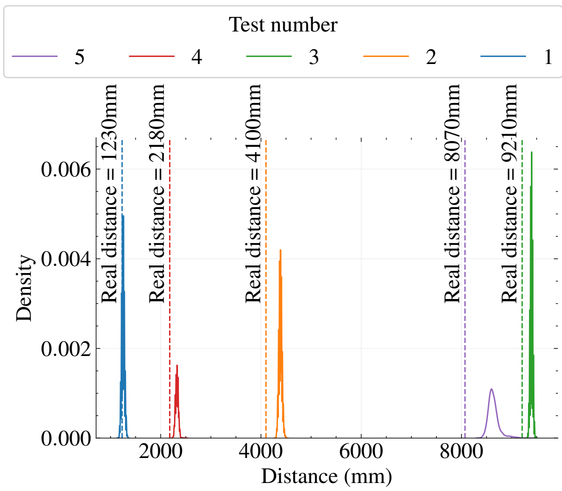

Figure 3. Probability density function of the measured distance. Dashed vertical lines represent the real distance.

properly addressed by the safety procedure. In any case, the detected error is in agreement with the considered technical specifications.

Finally, test number 5 was performed with the sensors in two different rooms, with walls, desks, doors and many other interfering objects placed among them. From Fig. 3 and Table I it is possible to see that measurements remain affected by the bias error, confirming that the absence of a direct path may worsen the measurement accuracy.

VI. Second test set: 2D localization for a possible safety scenario

A. System and algorithm presentation

In this section second session of tests, we considered an Ultra-Wideband band network including four well-known positioned and synchronized anchors and a device to localize, using the TDoA algorithm , with the standard synchronization algorithm implemented by the used module, which has factory closed source firmware. A representation of the network is given in Fig. 4 where A, B, C and D are the anchors, whereas T is the device to localize.

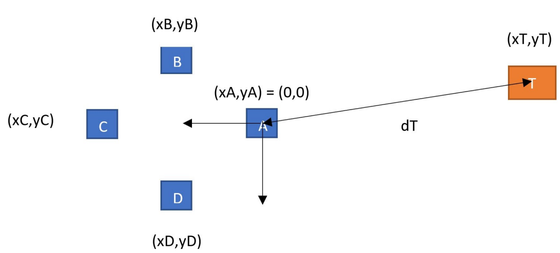

Figure 4. Network Topology

The distance of each couple $(anchor_i, Device_T)$ was measured in a configuration with some obstacles. Results are presented in Fig. 5 and Tab. II), respectively.

From the above measurements, it is not possible to identify the location of the device by simply finding the intersection

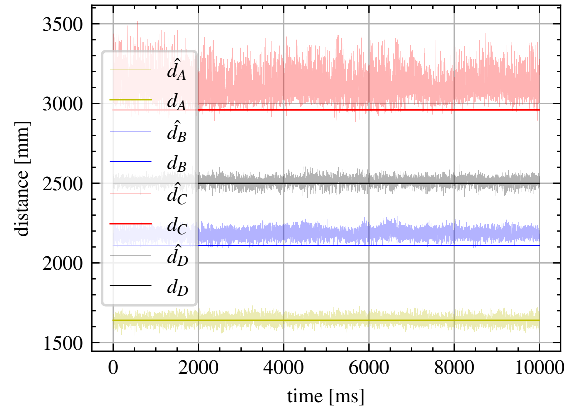

Figure 5. Characterization of each sensors with some obstacles

Table II
CHARACTERIZATION OF EACH SENSORS WITH SOME OBSTACLES

Sensor (#)	Real dist. (m)	Mean m. dist. (m)	Std. Dev. (m)	Mean Err (m)	Max Err (m)
A	1.64	1.641	0.024	0.001	0.092
B	2.11	2.183	0.028	0.073	0.185
C	2.96	3.108	0.082	0.148	0.558
D	2.50	2.512	0.023	0.012	0.118

of spheres with radius equal to the distances returned by the device and with the center equal to the (known) position of each anchors. An appealing alternative technique is represented by machine learning. However, for the intended applications, this is not a viable option. Indeed, the limited resource devices that are supposed to be used prevent the adoption of machine learning that, moreover, is discouraged in the context of functional safety [30]. Furthermore, the tight reaction times require a fast calculation of the device position. In addition, the application was designed to be configurable, with possibly different known distances between the anchors. For these reason a machine learning approach would require an important dataset and a long training session.

For these reasons, we propose an efficient deterministic algorithm for determining a 2D global position (Alg. 1). In particular the system is simplified in 2D, because the measurement errors shown with many obstacles and walls would cause an even larger error in the third dimension, and also to simplify the computation to ensure real-time performance.
The proposed algorithm, once obtained all the distances between anchors and tag, finds the 2D points which are intersection of all circumferences with radius equal to the distances returned by the sensor and with the center equal to the well–known position of each anchors. The position of the intersections is shown in Fig. 6.

After that, found at maximum n points, where $n = 2 * \binom{4}{2} = 2 * \frac{4!}{(4-2)!2!} = 12$, the algorithms finds the neighborhood, with center one of those point and with radius r, which contains the maximum number of points (Fig. 7). If all neighborhoods, with the described properties, contain one point, then the

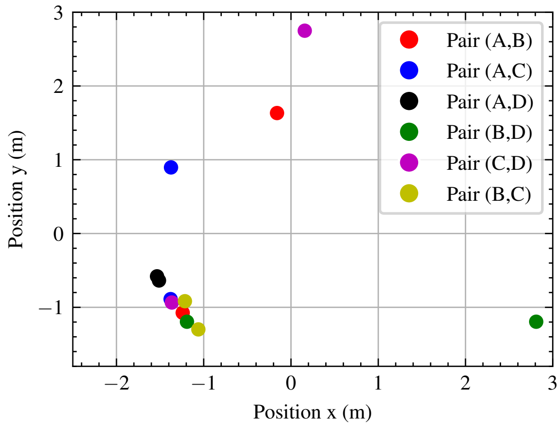

Figure 6. Intersection points of the circumferences for every sensors pairs

algorithm returns the neighborhood containing at least 2 points with center one of those point and with the smallest radius $r_n > r$. Once found the neighborhood, the mean point of those contained in the selected collection is returned.

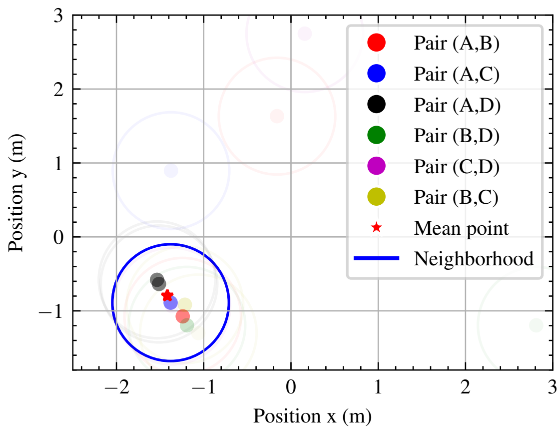

Figure 7. Example of the neighborhood chosen with the algorithm

B. Experimental results

The algorithm was tested in an experimental campaign with some obstacles between the anchors and the target device. Results are presented in Fig. 8 and in Table III respectively.

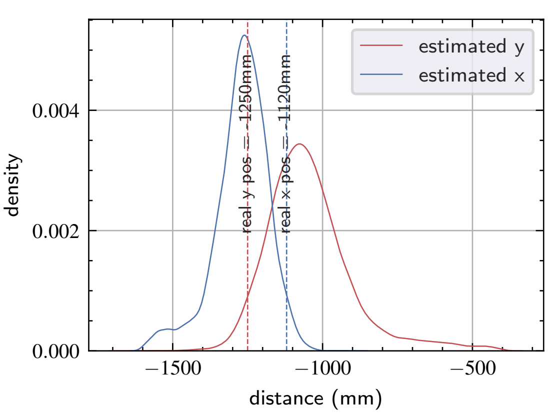

Figure 8. x and y coordinate estimation with some obstacles

As can be seen in Table III, the mean estimated position on each axis has a rather limited error resulting in a good estimation of the real position. Unfortunately, both maximum error and standard deviation are definitely too high. Indeed, as can be seen in Fig. 8, this effect is due to the superimposition of noisy peaks in the measured distance leading to overestimation of the real distance and thus high error and standard deviation. It appears evident that the algorithm itself does not provide satisfactory results in these terms and a further filtering procedure should be introduced. In particular, we assumed that a maximum distance, equal to a reasonably distance (0.5 m) that a person could travel in a sampling time (25 ms), between two consecutive points could be defined and that it is possible to discard a single anchor distance if identified as too noisy. The results filtering are shown in Table III, where the beneficial effects are evident. As can be seen, standard deviation, mean error and maximum error are decreased, leading to a more accurate estimation of the real distance with a maximum error lower than 50 centimeters, which results acceptable for the targeted applications.

Algorithm 1: Positioning(radius)

```
initialized Ax, Ay, Bx, By, Cx, Cy, Dx, Dy
measure(dAT,dBT,dCT,dDT)
listPoints ← []
for each couple of sensors (I, J) do
    Points_ij ← calculatePoint(Ix, Iy, Jx, Jy, dIT, dJT)
    listPoints.append(Points_ij[0])
    listPoints.append(Points_ij[1])
numPointInNeigh ← [],pointInNeigh ← []
maxNumNeigh ← 0, maxIndexNeigh ← −1
for i=0;i<len(listPoints);i++ do
    numPointInNeigh.append(1)
    pointInNeigh.append(listPoints[i])
    for p in (listPoints \ listPoints[i]) do
        dist ← calcDist(listPoints[i], p)
        if dist<r then
            numPointInNeigh[i]++
            pointInNeigh.append(p)
    if numPointInNeigh[i]>maxNumNeigh then
        maxNumNeigh ← numPointInNeigh[i]
        maxIndexNeigh ← i
if maxNumNeigh>1 then
    return calcMeanPoint(pointInNeigh[maxIndexNeigh])
else
    return Positioning(radius + 0.1)
```

Table III
COORDINATES ESTIMATION WITH SOME OBSTACLES

Test	Variable dist. (m)	Real dist. (m)	Mean m. Dev. (m)	Std. Err (m)	Mean Err (m)	Max Err (m)
no filter	x	-1.12	-1.253	0.076	0.133	0.526
	y	-1.25	-1.073	0.120	0.176	0.896
	$distance$	1.678	1.655	0.023	0.022	0.189
with filter	x	-1.12	-1.218	0.063	0.098	0.318
	y	-1.25	-1.134	0.094	0.115	0.484
	$distance$	1.678	1.668	0.026	0.010	0.161

Results were not compared with any machine learning approaches for the reasons proposed in the previous section and since, cause of the configurability of the system and the small dataset available, those techniques would probably overfit data, proposing an accurate and precise system for this configuration and data, but not for all the possible ones.

VII. Conclusions and Future Directions of Research

In this paper we addressed UWB performance in distance measurement and positioning for functional safety systems exploited by critical applications such as mobile robotics. Particularly, we described the outcomes of a measurement campaign carried out on commercial devices in indoor environments. The obtained results showed that both distance and position may be affected by a bias error, mainly due to the presence of obstacles. Nonetheless, such issues can be addressed, for example, by incorporating an appropriate filtering technique into the positioning algorithm. Overall, results are promising, since they cope with the requirements of the targeted applications. The whole experience allows to envisage some further interesting activities. In particular, both the localization algorithm and the filtering could be improved in order to achieve even better performance to meet the demands of more demanding applications. Furthermore, supplementary experiments could be carried out to characterize the system, particularly in terms of distance coverage, and to collect additional data to compare the obtained results with the ones obtained with other existing techniques. Finally, in the light of extending the application contexts, outdoor measurement campaigns need to be carried out.

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