Using a Movable RFID Antenna to Automatically Determine the Position and Orientation of Objects on a Tabletop

Steve Hinske[1] and Marc Langheinrich[2]

[1] Inst. for Pervasive Computing
ETH Zurich
8092 Zurich, Switzerland
steve.hinske at inf.ethz.ch
[2] Faculty of Informatics
University of Lugano (USI)
6904 Lugano, Switzerland
langheinrich at acm.org

Abstract. Augmented tabletop games support players by sensing the context of game figures (i.e., position and/or orientation) and then using this information to display additional game information, or to perform game related calculations. In our work we try to detect the position and orientation of game figures using small, unobtrusive passive RFID tags. In order to localize our multi-tagged objects, we use a small movable antenna mounted underneath the table to scan the game environment. While this approach is not capable of real-time positioning, it achieves a very high accuracy on the order of a few millimeters. This article describes our experimental setup, discusses the trade-off between speed and accuracy, and contrasts our approach with a multi-antenna setup.

Keywords: Radio-Frequency Identification (RFID), Object Detection, Miniature War Games, Localization.

1 Introduction

Using radio frequency identification (RFID) technology for detecting tagged objects on surfaces such as shelves or tables has been subject to some research in recent years. Scenarios such as smart shelves in retailing [1,3,10] or tabletop gaming applications [2,7] can greatly benefit from this unobtrusive localization and identification technique. For many applications, it suffices to know whether a given object is in read range of the antenna (i.e., whether the object is *there*), but some require further information such as where an object is exactly and maybe even how it is oriented.

Previous work on using RFID technology for determining the position of objects used multiple antennas organized in a specific way (e.g., a chessboard pattern) to collaboratively infer the exact position and orientation of multi-tagged objects [4,5]. While the reported prototypes were able to achieve an accuracy of a few centimeters,

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tabletop games typically require accuracy on the order of millimeters. In *miniature war games*, for example, two or more players engage in battle with each other, commanding an army of numerous game objects representing combat units. In such settings, measurements need to be as accurate and precise as possible in order to properly determine, for example, the visibility of enemies, or the range and effect of an attacker's weapon.

Usually, players of miniature war games use rulers and goniometers to measure the distances and angles between units and their orientation. Since these tasks can be laborious and time-consuming, our goal is to support the players by automatically capturing this information and providing it to them in an automated and unobtrusive fashion, allowing them focus on social interaction and on the game itself.

Throughout this paper, we will use the example of *Warhammer 40k*, a popular miniature war game that features numerous game units and landscape components scattered over a large table. Players stand around the table, positioning their units and measuring distances between these units, as shown in Fig. 1. As *Warhammer 40k* continuously requires precise information about the location and orientation of all game objects, it proves to be an excellent example application for a precise positioning system: in order to be of any value to the players, the system must be able to localize objects within a few millimeters.

Fig. 1. A typical Warhammer battlefield scene (from [5])

This paper reports on our investigation into the use of passive RFID technology to not only detect objects on a surface, but to also determine their exact position and orientation. This paper is structured as follows: first, we give a brief overview of localization techniques and elaborate on why RFID technology is beneficial for locating objects on a surface. Second, we describe our initial approach which utilizes an antenna grid to localize tagged objects. Based on these findings, we then propose a new infrastructure that uses only one movable antenna and significantly improves the localization accuracy. The paper is concluded with a short summary and discussion of the presented work.

2 The Benefits of Using RFID Technology

In [4,5] we previously discussed in detail the advantages and disadvantages of using RFID technology for determining the position and orientation of objects. We thus give only a brief summary here.

Compared to the technologies presented in Table 1, RFID technology has several advantages. When examining the working principle and features of (high frequency) RFID technology, it becomes apparent that [5]:

- the technology can be hidden and thus works unobtrusively (small tags),
- the objects are almost maintenance-free (except for exchanging damaged RFID tags),
- there is no need to calibrate the equipment,
- each object is uniquely and unambiguously identifiable,
- no line-of-sight is required, and
- costs are low by comparison.

In the context of a miniature war game, this particularly means that the objects can be moved freely on the surface, even if there are decorative elements. The technology is completely disguised (i.e., the RFID tags are invisibly embedded into the objects and the antenna grid is installed under a table), and can thus unobtrusively support the players' actions. Furthermore, the infrastructure is almost maintenance-free, as we do not need to calibrate the technology and the RFID tags do not need to be maintained or replaced. The calculation can be done by a computer with average computational power, which in turn means that the computer employed can be rather small and thus also be integrated in the environment. Additionally, we can scan many figures simultaneously and unambiguously identify them, which is not as easily possible with other localization techniques. Since the antennas induce a three-dimensional field, it is also possible to have game elements on the table that make the game map uneven or even represent "hovering" units (see Fig. 2 left) or taller buildings (e.g., hills, houses, etc.; see Fig. 2 center and right). Finally, RFID technology is comparably inexpensive compared to other technologies.

Table 1. Overview of the disadvantages of localization techniques for objects on tabletops

Technology / Approach	Disadvantages
Ultra-wideband (UWB) (e.g., [13])	• Not precise enough (within tens of centimeters) • Fixed infrastructure[1] • Rather big tags • Tags require batteries • Requires calibration • Expensive
Ultrasound (infrastructure) (e.g., [11])	• Fixed infrastructure • Tags too big • Tags require batteries • Very expensive
Ultrasound (no infrastructure) (e.g., [6])	• Tags too big • Tags require batteries
Load sensing (e.g., [9])	• Cannot identify objects • Not sensitive enough for lightweight objects • Requires totally flat surface
Infrared technology (e.g., [8])	• Requires line-of-sight (cf. Fig 2)
Visual recognition (e.g., [7])	• Cannot identify similar or equally looking objects (cf. Fig. 2) • Requires calibration • Requires computing power
Touch technology(e.g., [12])	• Requires calibration • Very expensive • Detection is based on capacitive coupling (through the human body)

The main disadvantage of RFID technology, however, is that it was simply not meant to be used for localization, not to mention orientation measuring, but solely for identification. And even when used for localization, it is typically limited to offering binary information only: one can only tell whether a specific object is in read range, but not where exactly[2].

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[1] *Fixed infrastructure* means here that the sensing devices are physically attached to the environment, for example, the walls or the ceiling (i.e., they cannot be (re-)moved easily). This does not hold true for our RFID *infrastructure*, which could be moved (as can, for example, a camera for visual recognition).

[2] There are readers that can either vary the power level or read the signal strength. The former approach is time-consuming while the latter is rather error-prone, due to possible distortion caused by reflections, multipath effects, etc. And, unfortunately, in both cases the readers are very expensive and thus unsuitable for most everyday applications.

Fig. 2. Objects that are not directly on the ground make it difficult for some position recognition techniques to work (left). Landscape elements (centre) do not work with sensing techniques that require a flat surface and/or line-of-sight. Video recognition does not work with many objects that look very similar, i.e., objects that do not have distinctive shapes (right).

3 Previous Work on Using RFID Technology for Localization

We previously reported on the development of an infrastructure that enabled the automatic and relatively precise tracking of the location and orientation of game objects on the playing field [4,5]. Our approach was to increase the number of antennas in order to exploit the information gained from the overlapping read ranges of the antennas. The general principle is shown in Fig. 3. The circles around the antennas symbolize their read range given a specific tag (the read range inter alia varies with the tag model). This modified version of the *cell of origin* approach allowed us to determine the position of a tag as follows: when an antenna reads a given tag, the grid increases an internal counter for each cell (the small white squares in Fig. 3) that is in range of this particular antenna. After completing the read cycles, the tag is most likely in (one of) the cells with the highest counters.

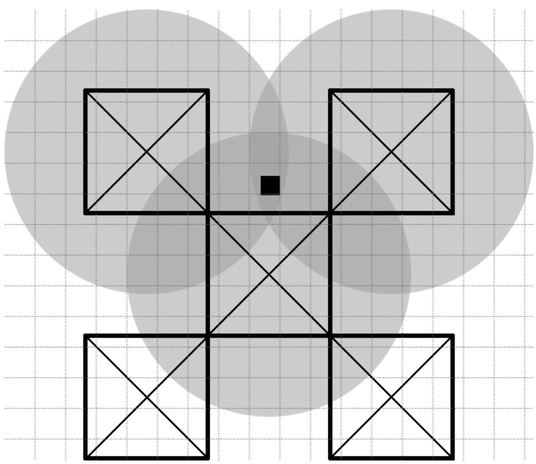

Fig. 3. Multi-antenna approach using multiple antennas organized in a grid (big squares with thick black lines) to determine the position of a tag (small black square) by measuring the overlapping areas of the read ranges (grey circles) (from [4]).

In Fig. 3, the dark area in the center marks the area where the tag, represented by the small black square, must be located. It is not possible to determine where exactly it is within this area. Therefore, the goal is to minimize this area of uncertainty. It is obvious that the size of the “uncertainty area” depends on the number and size of the read range circles (i.e., the antennas), and on the layout of the antenna grid. The smaller the read range circles, the more antennas there are and the denser the grid, the better.

To counter some technical deficiencies of the currently available equipment and the general problem of interference that RFID technology has to cope with (e.g., tags might not be read in a cycle, environmental interference such as metallic objects or even people, etc.), we experimented with several constellations of RFID tags and antennas and varied the following components:

- the layout of how the antennas are placed (design of the antenna grid),
- the RFID antenna model,
- the RFID tag, and
- the read range of the employed reader.

An automated test environment was used to investigate how the variation of these components influences the preciseness of the readings, using two antenna models (FEIG ID ISC.ANT 100/100 and FEIG ID ISC.ANT 40/30), and two different RFID tags. After measuring the range in which each tag could be read by the reader, eight antennas were arranged in a chessboard pattern (see Fig. 4) and a number of objects were tagged with several RFID tags and placed onto the field.

A single reader (FEIG ID ISC.MR 101-A) was connected to the antennas via a multiplexer (FEIG ISC.ANT.MUX 8), which sequentially energizes the individual

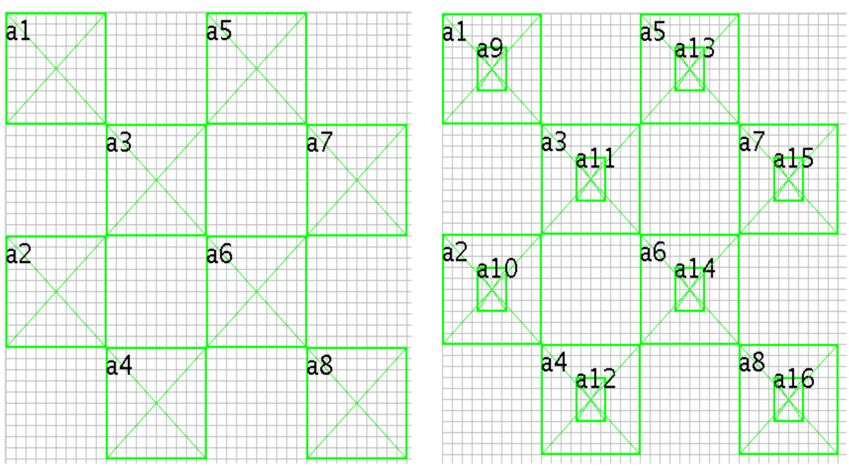

Fig. 4. The two different antenna grid layouts used in [5]. The grid on the left consists of eight 10x10 centimetres antennas, while the one on the right uses eight additional antennas that are considerably smaller (3x4 centimetres) and placed on top of the bigger antennas (from [5]).

antennas to return the read tags in range. After several read cycles (one read cycle took approximately 2-3 seconds) that helped to avoid erroneous read data, our system determined the highest probability for each scanned tag on the board. Based on this data and the known shape and size of each object, the estimated position and orientation of the game figures was then calculated and displayed.

The results as reported in [5] showed that the best estimates of the scanned tags were within a deviation of 3-4 centimeters, rendering this approach insufficient for game applications like miniature war games that require a resolution of less than one centimeter.

4 Improving Resolution Accuracy Using Moveable Antennas

While previous work showed that it is in principle possible to use off-the-shelf RFID technology for determining the position of objects, increasing the accuracy of a multi-antenna approach seems difficult: in order to improve localization results, the antennas would either need to be moved closer together, or smaller antennas would need to be used. Increasing antenna density quickly conflicts with the nature of RF fields: if the antennas are too close together, the field induced by one antenna will be inexorably extended by the coils in the adjacent antennas (i.e., an antenna might then discover a tag that is actually near the coil of another antenna). Using smaller antennas would not only require a lot more antennas (and thus also more readers and multiplexers to power them) to cover an area of the same size, but also limit overall detection rates due to the much smaller read ranges of each individual antenna.

To still benefit from the many advantages of RFID technology and yet compensate the insufficient accuracy, we thus propose a different approach: instead of using many antennas in a grid, we use only one antenna that will be moved across the area. This single antenna will continuously read what RFID tags are in range. This information, combined with the current location of the antenna, can then be used localize the individual RFID tags. In contrast to a multi-antenna approach, this solution has the obvious drawback of requiring more time to cover the same area. However, since tabletop war games do not require real-time positioning[3], a certain period of scanning time migh be perfectly acceptable.

Using a LEGO MindStorms NXT robotic set[4], we constructed a test environment in which a robot controls a slide carriage attached to two orthogonal track systems (see Fig. 5). The RFID antenna (FEIG ID ISC.ANT 40/30) on top of the carriage can then be moved across the surface with an accuracy of a few millimeters. The size of our test bed is ca. 40x50 centimeters (see Fig. 6). The FEIG ID ISC.MR101-A reader antenna can power the antenna every 250ms, which means four read cycles per second. The carriage moves in a zigzag fashion across the board, i.e., it moves along the x-axis to the end of the surface, advances on the y-axis for 1cm, moves back along the x-axis, and so forth.

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[3] Miniature war games, as most other tabletop games, are turn-based; in fact, one turn can easily take up several minutes.

[4] http://mindstorms.lego.com/

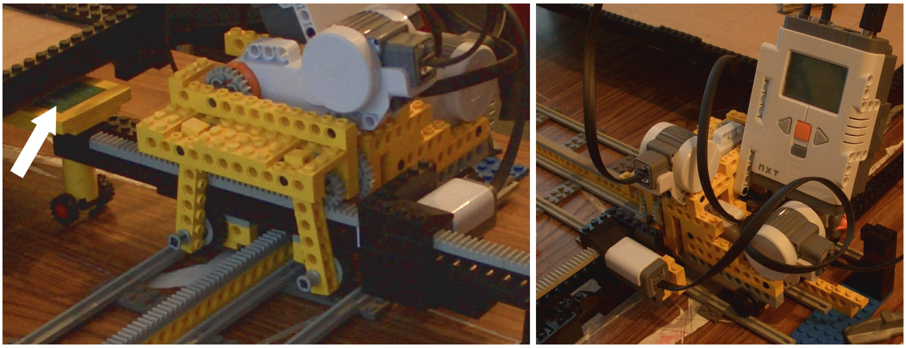

Fig. 5. The robot moves the carriage with the antenna (see white arrow) using two orthogonal track systems (left). The NXT control unit is connected to a computer (right).

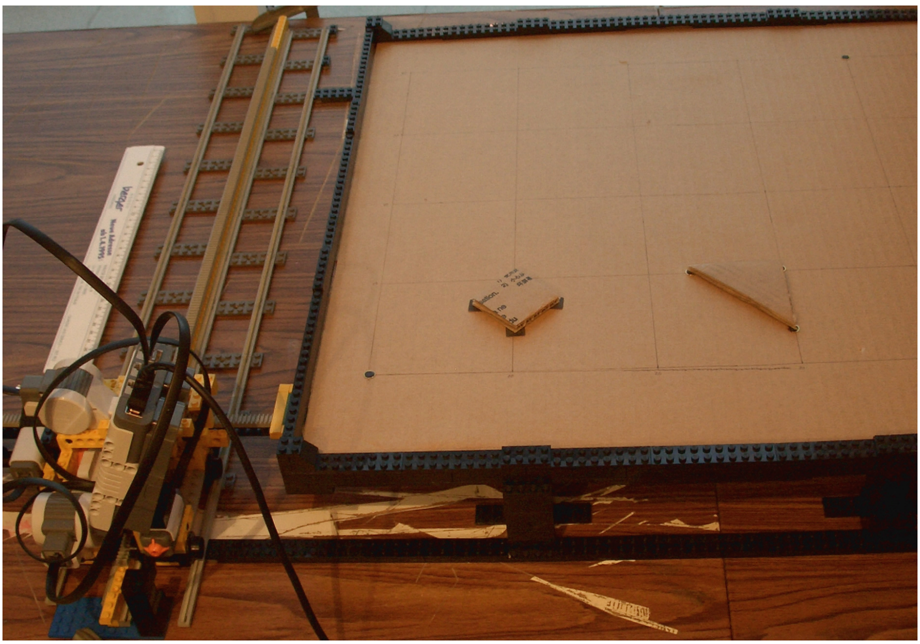

Fig. 6. The test environment with the robot, the carriage, and the tracks as well as the cardboard surface with two test objects. The two objects have RFID transponders attached to each of their corners.

Since the carriage is moved by a cogwheel on a track with small cogs (see Fig. 5), it is not possible to indicate the speed in a distance-time relation (e.g., in cm/s) but only in degrees determined by the rotation of the motor. The motor could be controlled in ten steps (10% to 100% of the max. power output), resulting in different velocities of the carriage (see Fig. 7), which also influences the number of possible measurements, since we can energize the antenna at a rate of 4Hz (see Fig. 8).

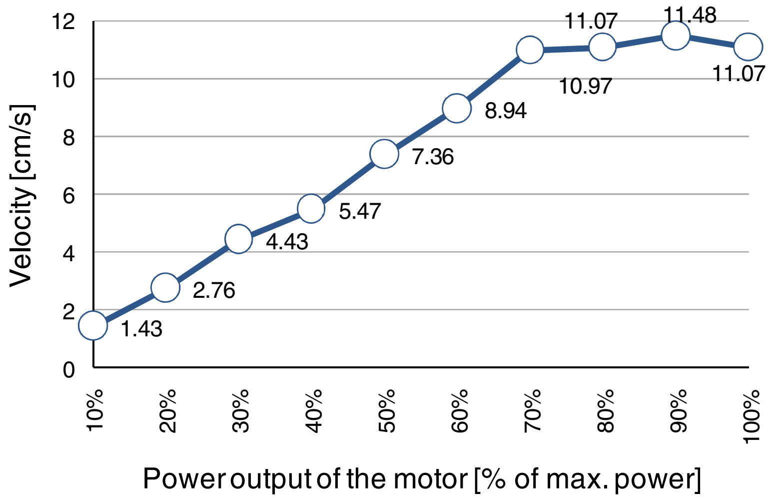

Fig. 7. The velocity of the carriage in dependence on the power output of the motor

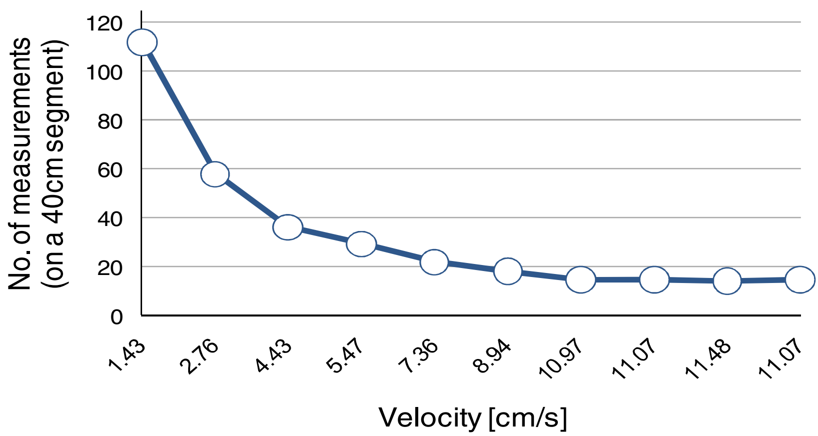

Fig. 8. The number of possible measurements in relation to the velocity

We began our test series by placing two RFID transponders at designated X-Y locations on the test surface: they were positioned at 20cm/10cm and 30cm/30cm, respectively, with the lower left corner being the point of origin. Starting from the zero-point, the carriage would then run over the whole area with a velocity of ca. 4.4cm/s (this initial value was chosen to guarantee approximately one read cycle per cm). We ran the test series five times. Tables 2 and 3 summarize the results.

It is worth noticing that the deviation on the y-axis was constant in each case, but there is a simple explanation for this: while the antenna constantly moves along the x-axis (which elucidates the varying x-values), the y-axis remains fix und thus the deviation constant. In general, with average deviation being between 0.1 and 0.2 centimeters, the measurements were extremely accurate, exceeding our expectations by far: our system

Table 2. Results for the 20/10 coordinates. All values are in centimeter.

	Absolute value of measurement		Deviation (unsigned)	
	x	y	x	y
1	20.1	9.8	0.1	0.2
2	20.0	9.8	0.0	0.2
3	20.0	9.8	0.0	0.2
4	20.1	9.8	0.1	0.2
5	20.1	9.8	0.1	0.2

Table 3. Results for the 30/30. All values are in centimeters.

	Absolute value of measurement		Deviation (unsigned)	
	x	y	x	y
1	30.0	29.9	0.0	0.1
2	30.1	29.9	0.1	0.1
3	30.0	29.9	0.0	0.1
4	30.0	29.9	0.0	0.1
5	30.2	29.9	0.2	0.1

could in most cases determine where a transponder is located with a precision on the order of a few millimeters.

Unfortunately, regardless of this almost perfect accuracy, there was a severe downside: each test round took approx. 11 minutes (ca. 13 seconds for scanning the x-axis incl. adjustment time multiplied by 50 rows), which even without real-time requirements might render this approach infeasible for most practical applications. We therefore intended to considerably shorten the time it takes to scan the surface area, though we knew that increasing the speed of the carriage would lower accuracy due to fewer measurements (see Fig. 8). The aim was to determine the trade-off between the costs (i.e., the loss of accuracy) and the benefits (i.e., shorter read times). To this end, we repeated the previous test series with different velocities and calculated the mean deviation for each velocity. The results are summarized in Fig. 9.

In general, slower speeds show a lower average positioning error. The minor exceptions at velocities of 2.76cm/s and 4.43cm/s seem to result from natural oscillation of the motor when rotating with lower frequencies (the loss of accuracy is also only about 1 millimeter). However, the error increases with higher speeds and reaches some 5 millimeters at velocities of around 11cm/s. The boundary seems to lie at a velocity of 7.36cm/s, which corresponds to a power output of 50%. In this case, scanning an area the size of our test surface (40x50cm) took approximately 7.5min Apparently, it is not possible to further reduce this time with our test setup.

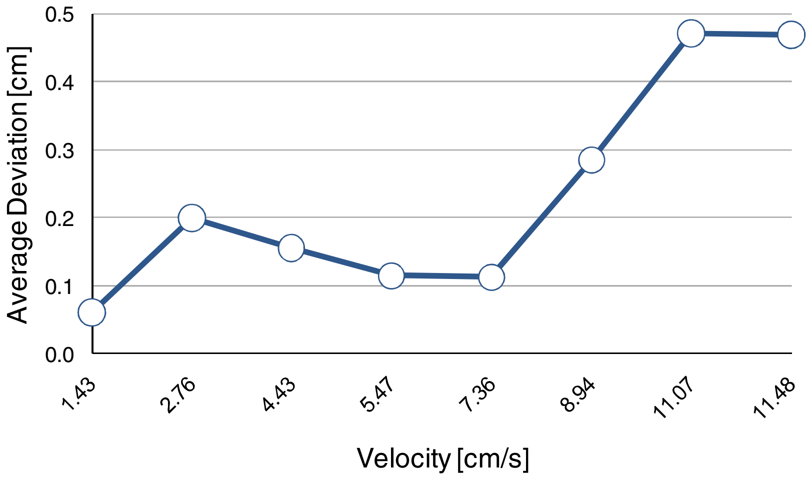

Fig. 9. The average deviation against the velocity

5 Conclusions

In this paper we presented a novel approach to determine the position and orientation of objects using RFID technology. Based on the example of a miniature war game, we demonstrated the idea of using an antenna that is attached to a slide carriage which moves the antenna over (or rather under) a surface with tagged objects. Calculating the position of each single tag using the overlapping read ranges at each reading position of the antenna allows us to estimate where the object is approximately positioned, and thus, in the case of multi-tagging, how it is oriented. As far as we know, there is currently no other sensing infrastructure that is capable of such high accuracy (except for visual recognition, which fails at differentiating equally looking objects though). In principle, it is possible to cover even very large tables by simply sectioning it and applying one scanning set-up to each section.

The downside clearly is the time required for scanning an area. The main objective for future work would thus be to significantly diminish the scan time. Currently, we see two options to achieve this:

- First, we could use a slightly modified version that minimizes the idle read time in which the antenna does not read any transponders (i.e., the time between the reading of one tag and the next one). Consequently, we have to increase the velocity in between transponders, which can be done as follows: we move the carriage with full speed (ca. 11.5cm/s) along every fourth x-axis, omitting three rows, and, if we read at least one tag on the way, we move over the same section again at a slower velocity. Preliminary tests revealed that the time could be significantly reduced to approx. 4.5min while the average deviation was only slightly worse. This approach, however, very much depends on the on the scarcity and distribution of the objects on the surface: with a high number and density of objects, this approach will presumably take longer than with the "naive" version. More tests will need to be conducted to evaluate this properly.

- Second, we could simply split the area into smaller sections and use one antenna for each section. If the sections are, for example, 20x20cm, the time required could be reduced to approx. one minute, which is undoubtedly fast enough for most turn-based games and many other applications (e.g., a smart shelf in a store). In addition to that, we would still need considerably less antennas compared to the antenna-grid approach.

Nonetheless, this proposed localization technique cannot be used for real-time applications, in contrast to other technologies (e.g., visual recognition or ultrasound). Our approach is furthermore subject to criticism in three more points. First, the selection of the individual components (RFID readers, antennas, and tags) is very crucial: if we substitute only one component, the results are at least distorted, if not totally different, requiring re-calibration. Second, RFID does not work too well with metallic objects and environments: metal biases the read rate of readers and tags. Third, we will also need to verify the influence of other game objects on item detection, e.g., houses or hills that figures are placed in or on, which increase the distance between the surface and the tag.

These disadvantages notwithstanding, it seems that this approach based on RFID technology is a promising candidate for localizing objects on a surface: the high accuracy of about 1 millimeter, combined with the inherent advantages of RFID technology (e.g., a completely invisible and unobtrusive scanning infrastructure that also allows for uniquely and unambiguously identifying all objects) promises cheap high resolution localization for augmented tabletop games in the near future. And though augmented tabletop games admittedly are a prime example, one can envision other domains that could benefit from such a high resolution, e.g., architectural and city planning applications that involve 3-dimensional models arranged on a tabletop.

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