RFIDice – Augmenting Tabletop Dice with RFID

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ABSTRACT

Augmented dice allow players of tabletop games to have the result of a roll be automatically recorded by a computer, e.g., for supporting strategy games. We have built a set of three augmented-dice-prototypes based on radio frequency identification (RFID) technology, which allows us to build robust, cheap, and small augmented dice. Using a corresponding readout infrastructure and a sample application, we have evaluated our approach and show its advantages over other dice augmentation methods discussed in the literature.

Keywords

Augmented Dice, RFID, Pervasive Computing, Pervasive Games, Tabletop

1 INTRODUCTION

Dice are an integral part of many traditional games: whenever a random component is required, people usually rely on dice. Thousands of existing games employ one or more dice, either as a part of the game (e.g., Monopoly) or as the core game element (e.g., Yathzee or Craps). In all cases, the dice are rolled on a flat surface, usually a table, and the sum of all eyes or the particular pattern rolled (e.g., a “street”) advances the game in some way. There are numerous different kinds of dice (e.g., eight- or ten-sided dice) with the six-sided die, also called D6 (cf. D8, D10, etc.), being the most commonly used one. In this paper we focus on the D6 with numbers (or dots) from one to six, each assigned to a designated side of the die.

While virtually any game can be transferred to and played in the virtual world (i.e., a video or computer game), thus offering countless new game options, people nonetheless continue to enjoy (and often prefer) playing “traditional” games. One reason for this is certainly the social aspect of gaming: coming together in order to chat, compete, banter, and laugh together plays a significant role in human culture that solitary (and even on-line) video games cannot provide. Another important factor is also the haptic and spatial experience of moving markers, sorting cards, or manipulating game elements (e.g., in Jenga). Dice or spinning wheels in particular give the user both the excitement of watching the spin or toss converge on a lucky number, and the sense of actually being able to control this process, e.g., by a particularly vigorous throw or spin.

Augmented toys or pervasive games attempt to combine these two aspects – the physical sensation of game play and the close social interaction with other players – with the extended features and automated support known from video games. Through clever use of advanced sensing and communication technologies, computers can be embedded into the gaming environment and, due to the continuous miniaturization of these technological components, even into individual game pieces, and map the users’ real-world activities onto a virtual game model that can in turn drive displays or other game elements.

In this paper we present RFIDice, traditional D6 dice that contain RFID technology in order to automatically detect the value of a dice throw (i.e., the values facing upwards at the end of a roll). Since the technology is invisibly integrated into both dice and the gaming environment, players can continue to use the dice in their game in a traditional fashion. In order to evaluate the suitability of our approach, we constructed three wooden prototypes that were equipped with RFID tags on each (in-)side, and tested these dice in our test environment.

This paper is organized as follows: Chapter 2 introduces the general idea, motivates our decision to use RFID technology, and outlines the challenges deriving from this approach. Chapter 3 describes the technical realization of our three RFIDice prototypes, while Chapter 4 outlines our experimental setup and reports the results of our evaluation. We conclude with a summary and an outline for future work in Chapter 5.

2 CONCEPTUAL APPROACH

The basic approach for using RFID to detect the value of a die is quite simple: we add RFID tags to each inner side of a traditional D6 and embed an RFID antenna in the table surface. By detecting the tag that comes to rest on the antenna, we know the side that is facing down and can thus infer the side of the die that is currently facing up. This information can then be fed into the game system, where it might simply be displayed on a screen or actually trigger a specific action.

Since we focus on augmented traditional dice, approaches that rely on a virtual realization of dice (i.e., an application or device simply displaying a result, e.g. [4]) are not an option. Our goal is to provide players with a Tangible User Interface (TUI) in a form factor that they are used to and which they feel comfortable using [2, 3, 8]. Moreover, the augmentation of the dice should support users in an unobtrusive fashion, i.e., the dice should be enhanced in such a way that players do not even notice this modification.

Based on these general requirements, we infer three main goals for augmented dice:

- Rolling augmented dice must feel the same as rolling traditional dice,
- Augmented dice must still be usable in the "old-fashioned" way if the technology is switched off, and
- The detection system must be hidden and unobtrusive.

There are several possibilities for implementing an augmented die, i.e., automatically detecting the result of a roll. Eriksson et al. [1] present an overview of several approaches on how to realize an automatic acquisition of the eyes of a rolled die. Their six proposed approaches can be categorized as follows:

- A *visual approach* could use a photo scanner as a (see-through) dice table, with a piezoelectric or electret microphone on the glass. The microphone would then detect when dice have been rolled and initiate the scanning process. Image recognition could identify the sides of the dice facing down and infer the corresponding values on top. Instead of a scanner, a camera could also be used. To aid in image recognition, the individual dots or numbers on each side of a die could be painted with a UV or IR reflective color, which could be more easily detected using a corresponding UV or IR light being reflected.
- An *internal sensors approach* would integrate a small processor, an accelerometer, a transmitter, and a power source into the die. The accelerometer would be used to detect when the die has been rolled and read its orientation. The transmitter would then be awakened from sleep mode and send the detected orientation to a receiver. Power would come from batteries, or alternatively from harvesting the motion of the die. Instead of using accelerometers, direct contact to a metallic surface could be detected and, depending on different resistors connected to each side, the current side facing the table be identified.
- In the *external sensors approach*, Eriksson et al. propose to use RFID tags on each side and roll the dice on a reader antenna. In order to prevent the readout of the tag on top, they suggest integrating an interfering metallic core in the center.

Using cameras or scanners obviously is intruding since these devices require line-of-sight and must be placed in such a way that they have constant visual contact to the dice. The big advantage, however, is that dice would not need to be modified (except for using some reflective coating for the dots).

Dice equipped with internal sensors do not require a carefully controlled recognition environment, but the integrated technology might make a die unhandy and, for the time being, considerably bigger in size. The biggest drawback would be the internal power source, which would require frequent maintenance (i.e., exchanging the batteries); see, for example, [7].

In [6] ToolStone is presented, a small cube-like input device with the size of 2.5 x 4 x 5 centimeters that uses integrated coils to determine orientation and position of the device. This approach is very interesting since it does not require an internal power source. The necessary energy is provided by a WACOM tablet by emitting magneto-electric signals (the coils with a specific resonance parameter respond to this signal). There are, however, two disadvantages as far as our goal is concerned: first, the device is still too big to serve as an adequate replacement for traditional dice, and second, the dice must be rolled on designated area that cannot be hidden (WACOM tablet).

Using RFID technology for external detection seems to combine the advantages of the aforementioned approaches without carrying too much of their drawbacks. An RFID-based solution is maintenance-free and the detection devices can be invisibly integrated into the environment (e.g., an antenna placed underneath a table). In particular, RFID technology offers the following benefits:

- Low overall hardware costs (standard RFID equipment is continuously falling in price),
- No maintenance costs for dice (e.g., batteries, sensor calibration),
- Good integration into the environment (e.g. table),
- Small on-die footprint (both size and weight),
- Easy die manufacturing (many options for RFID tag packaging), and
- Little software costs (standard RFID software).

Nonetheless, as easy as the idea sounds, as difficult the realization turns out to be in practice. This is because tag detection depends on a large number of factors, such as

- Magnetic / metallic / liquid components in range,
- Size of the reader antenna,
- Size of the tag antenna, and
- Power (field strength) of the reader.

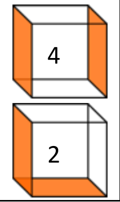
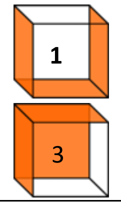
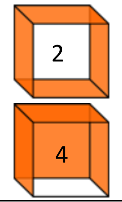
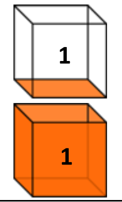
While antenna sizes can be reliably controlled, most other parameters might exhibit a high variability in a non-laboratory setting. In order to ensure tag detection, some safety margin thus needs to be taken into account. This, however, raises the potential for "overshooting", i.e., detecting more than just the tag at the bottom of the die, such as one on the side, or even the tag on top. Since standard RFID equipment does not allow for a detailed signal-strength analysis, only the presence or absence of a particular tag ID can be detected – not its orientation relative to the reader. Similar problems are described in [5], but, unfortunately, they do not provide specific details on how these problems are encountered.

To counter this problem, we therefore add a metallic layer inside the die to prevent our reader field from picking up tags on the side or at the top of our die (cf. [1]). The exact implementation of this metallic shield needs to be carefully evaluated, in order to find settings that shield unnecessary tags without preventing detection of the target tag (i.e., the one at the bottom).

But even with such a layer, we still expect to read more than one tag in the majority of the rolls. In such cases, IDs alone will not allow us to deduce the orientation of the die. In fact, we need to take both field propagation and the spatial orientation of the die into account. This leads us to make the following sets of assumptions.

- *Reader Field:* at the outset, we assume that tags at the bottom of the die will be more likely to be read out than those on the sides of the die. The tag on top of the die will be least likely to be read out, while tags on the side of the die will be read more likely than the one on top, but less likely than the tag at the bottom. Also, due to the nature of the magnetic field and the physical shape of a D6, it is more likely that two tags from opposite sides are being read (as they are equally aligned within the field of the reader), instead of two tags from adjacent sides (which are arranged in a 90º angle).
- *Spatial Distribution:* stemming from the physical layout of the used die (in our case a D6), we can infer spatial relations between tags if more than one tag is being read. Tab. 1 shows the two possible configurations each for 2, 3, and 4 tags. Knowing that the sum of opposite sides on a D6 totals 7 (i.e., 6-1, 2-5, and 3-4), we can exactly identify in which positions the *n* tags that have been read are arranged on the die.[1] Note that when reading 1, 5, or 6 tags, only a single possible configuration exists in each case (configuration for 6 tags is not shown in Tab. 1).

Table 1: No. of possible configurations when multiple tags are read (shown inside cube).

2 Tags	3 Tags	4 Tags	1/5 Tags
			

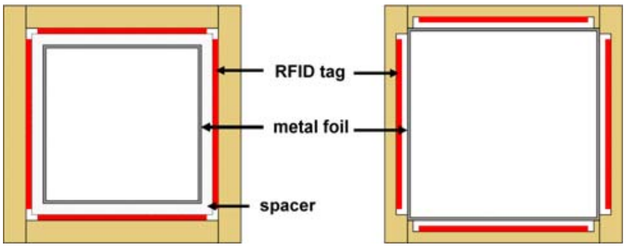


Figure 1: "Normal" die with metal foil and non-conductive spacer (left), and a "milled out" version with "sunken" tags (right). Both are equipped with the metal foil, but the milled out die does not require a separate spacer, since the metal foil sits over the milled out tag cavities like a lid.

Taking the spatial distribution and the field characteristics into account, we can create the following heuristics (cf. Table 1) for the individual number of tags read:

1. If only one tag is read, our field heuristics infer that it is the tag at the bottom of the die. The value on top is thus simply the opposite number from our identified tag.
2. If two tags are read, our field heuristic does not help us decide which side of the die is on top. If we read two adjacent sides, we would assume that one of them is currently at the bottom, which would still leave two options for the top value. If the two tags identify opposite sides, we would assume that none of the two is actually at the bottom (as this would mean that we have read the top tag, which we assume to be unlikely). Assuming those two tags form the side of the die, we are left with four possible faces that could lie on top.
3. If three tags are read, they are either arranged around a common corner, or in a continuous band. With three tags around a corner, any of them could lie on the bottom, thus leaving us with three options for the top value. However, if those three values are along a continuous band, we assume that the middle one is the bottom (as per our field heuristics) and that the other two are on the sides. This allows us to infer a top value.
4. With four tags, we again can differentiate between a corner configuration and a continuous band one. Neither one allows us to draw conclusions for the top value, however. Assuming that the bottom tag is read and that the top one is not read, we still have two choices for the corner configuration. In a continuous band configuration, our field heuristic assumes that neither top nor bottom tag have been read (which leaves two choices).
5. There is only one configuration for five tags, and assuming that the top tag is the least likely one to

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[1] For other types of dice, similar heuristics often hold.

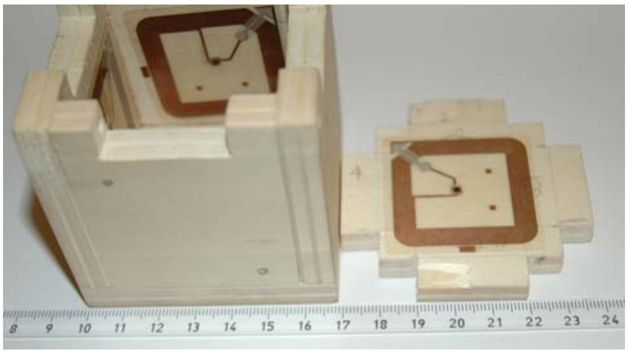


Figure 3: The large normal die with the lid open, revealing the enclosed RFID tags. The scale on the ruler is centimeter.

be read, we can conclude that the missing tag is facing top.

6. Should we read all six tags, the die could be oriented in any of the six possible orientations.

Obviously, adding the component of uncertainty to this approach is certainly not very satisfying. We will, however, demonstrate that the success rate of determining the right side of the die is rather high.

3 TECHNICAL REALIZATION

We constructed three dice of different size, all made out of plywood, two “normal” dice in two different sizes (large and small), and one “milled out” version (large). All dice contain six RFID tags each, shielded by metal foil and optionally separated from the foil by a non-conductive spacer material. Each die can easily be opened, in order to change the metal foil and the spacer. The RFID tags are attached from the inside to each of the six sides. Fig. 1 displays the conceptual cross section of the two concepts.

The large normal die is 7 cm on each side, using 1 cm strong plywood. We attached six 13.56 MHz RFID tags with a size of 5x5 cm to each of its inner sides (see Fig. 2).

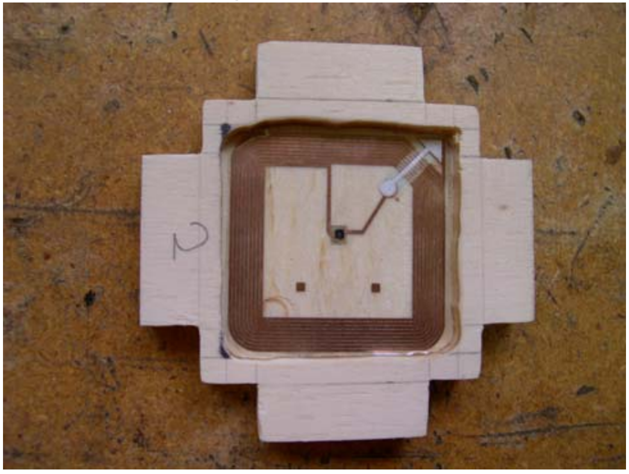


Figure 4: One side of the milled-out die disclosing the attached RFID tags.

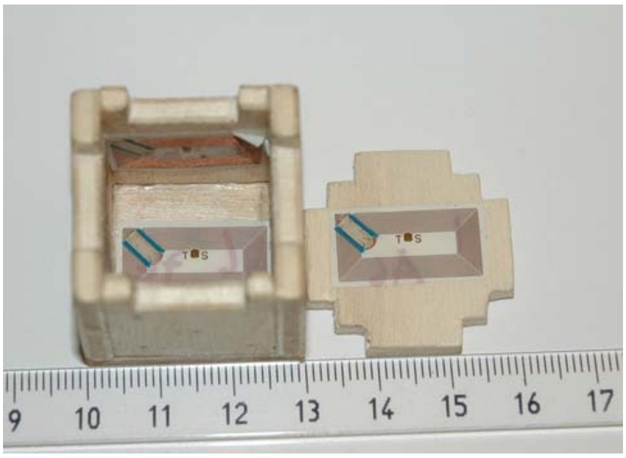


Figure 2: The small die opened up disclosing the attached RFID tags. The scale on the ruler is centimeter.

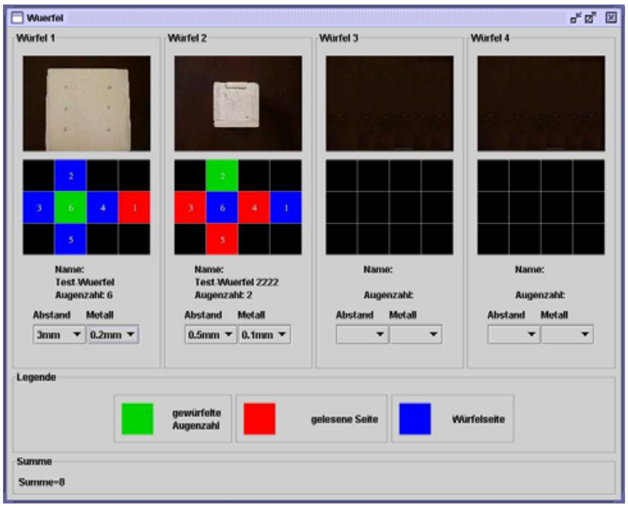
The milled out die is identical in size, but uses tag cavities on each side (see Fig. 3), in order to dispense with the separate spacer material. This “natural” distance between the tag and the metal foil also reduces the combinational variations of using different spacer materials (cf. Chap. 4).

The small die is only 3 cm on each side, which comes closer in size to a traditional D6, and uses 13.56 MHz RFID tags with a size of 1x2 cm (see Fig. 4).

As we pointed out before, the problem when using RFID to identify the bottom side of a die is that we do not have distance measurements at our disposal. If any of the other RFID tags is detected (e.g., one on the sides, or even the one on top), we cannot discern the one at the bottom from any of the others. Our primary goal is therefore to minimize the chances of reading any RFID tag *but* the bottom one.

To achieve this, we added a metallic foil to the center of each die that should shield all tags other than the one at the bottom from the field of the reader (see Fig. 5). An additional non-conductive spacer element ensures that the shielding does not directly touch any of the tags, as this would disable the tag completely, even at the bottom.

Figure 5: One of the cardboard spacers for the big die that keeps the metal foils separated from the RFID tags.



Würfel 1: Name: Test-Wuerfel, Augenzahl: 6, Abstand 3mm, Metall 0.2mm

Würfel 2: Name: Test-Wuerfel 2222, Augenzahl: 2, Abstand 0.5mm, Metall 0.1mm

Würfel 3: Name:, Augenzahl:, Abstand, Metall

Würfel 4: Name:, Augenzahl:, Abstand, Metall

Summe: Summe=8

Figure 6: Screenshot of the testing application.

4 EVALUATION

We tested each die in a number of different configurations (i.e., varying the thickness of both the metal foil and the separating spacer) in order to determine an optimal setup. In total, we rolled our dice 3756 times.

4.1 Test Environment and Settings

In order to easily conduct test series consisting of several thousands rolls, we developed an application that displays the detected dice and allows the evaluator to manually verify its correctness by comparison. The application is capable of displaying the results of up to four dice in parallel (this could easily be extended but suffices for now). A screenshot can be seen in Fig. 6.

We employed the following hardware components:

- FEIG ID ISC.MR101-A Mid Range Reader, HF 13.56 MHz,
- FEIG ID ISC.ANT340/240-A, 34x24 cm antenna,
- FEIG ID ISC.ANT.MUX 8-times multiplexer, and
- FEIG ID ISC.ANT100/100-A, 10x10 cm antenna.

We conducted the tests with two different metal foils and four different spacer widths (i.e., distances between the metal foil and the RFID tags). Preliminary tests showed that metal foils thicker than 0.2 mm resulted in no tags being read at all, while foils thinner than 0.1 mm resulted in all tags being read (not to mention the difficult construction due to the sensitive and brittle material). These results were more or less independent of the distances used between the foil and the tags. Thus, given these particular tags and readers as well our preliminary findings, we concentrated on evaluating only metal foils of 0.1 and 0.2 mm thickness. In the case of the milled out die, we only used the 0.2 mm strong metal foil, as the 0.1 mm foil produced very poor recognition rates.

To prevent the metal foil from coming too close to the RFID tags (which, as pointed out before, would disable them completely), we needed to position the foil at a certain distance from them. This was realized by using spacer material between the foil and the tag.[2] The material, of course, may not significantly influence the RF field (i.e., the material must be easily penetrable by radio waves). Since the distance influences readability, we tested four different widths (see Tab. 2).

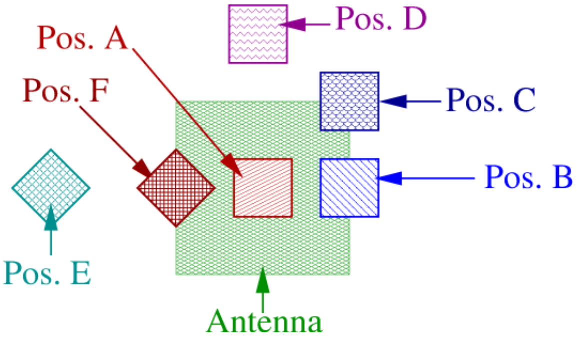


Figure 7: The different positions on the antenna that were tested to evaluate the homogeneity of the RF field.

Table 2: Tested Configurations Overview

Metal Foil	Spacer
0.1 mm	0.5 mm Cardboard
0.2 mm	1.0 mm Cardboard
	1.5 mm Cardboard
	3.0 mm Plastic foam

We first investigated detection rates for the different dice at different positions relative to the 10x10 cm antenna, in order to better assess the effect of the RF field. Fig. 7 shows the six different positions that we tested:

- A: center of the antenna,
- B: edge of antenna, orientation of the die parallel to the antenna,
- C: corner of the antenna,
- D: outside the antenna (approx. 3-5 cm away), orientation of the die parallel to the antenna,
- E: outside the antenna (approx. 3-5 cm away), orientation of the die diagonal to the antenna, and
- F: edge of the antenna, orientation of the die diagonal to the antenna.

For each measurement we positioned the die on the antenna at the given position, with a particular side on top. Based on the read RFID tags we then compared the detected side with the actual side. If multiple sides were detected (see our discussion in Chapter 2 above), we noted a failed result, unless our heuristic would give us a single reply (cf. Table 1). We performed this experiment with all three dice, on each side, at each position A-F, and with all possible configurations shown in Table 3 (actually, the milled out

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[2] The milled out die does not require a spacer (see Fig. 1).

die required merely one configurations since we only the 0.2 mm metal foil (see discussion above) and due to the "natural" (fixed) spacer). In total, 2448 measurements were taken (cf. Table 3). The results are presented in section 4.2 below.

During this first experiment, we accidentally placed the antenna on a metallic table for some of the combinations. While we quickly noted that the measurements where off, we were surprised to see that they seemed to be partly better than our wooden table that was used for the rest of the measurements.

Table 3: Number of measurements taken to test the influence of different die positions (relative to the antenna) on the overall detection rate

Die	Combinations	Rolls
Large / Small each	6 positions 6 die sides 2 metal foils 4 distances 4 measurements	1152 per die
Milled-out	6 positions 6 die sides 4 measurements	144
Total number of measurements taken:		**2448**

We therefore took a set of 288 additional measurements on this metallic surface, using the two normal dice with a fixed foil thickness of 0.2 mm and the 1.0 mm spacer (see Tab. 4).

Table 4: The number of measurements taken to test the influence of a metallic surface on the detection rate (using a 0.2 mm foil and a 1.0 mm spacer)

Die	Combinations	Rolls
Large / Small each	6 positions 6 die sides 4 measurements	144 per die
Total number of measurements taken:		**288**

We finally tested the results of randomly rolled dice. For this, we placed the large antenna on a wooden table and covered it with a cloth, in order to prevent the antenna from being damaged by the rolled dice. We rolled each die 30 times in each configuration, resulting in 510 rolls total (cf. Table 6).

We then replaced the single antenna with a set of 8 smaller (i.e., 10x10 cm) antennas, connected through a multiplexer to our single reader. We repeated the above experiment with the antenna array, resulting in another 510 rolls. Tab. 5 summarizes this experiment.

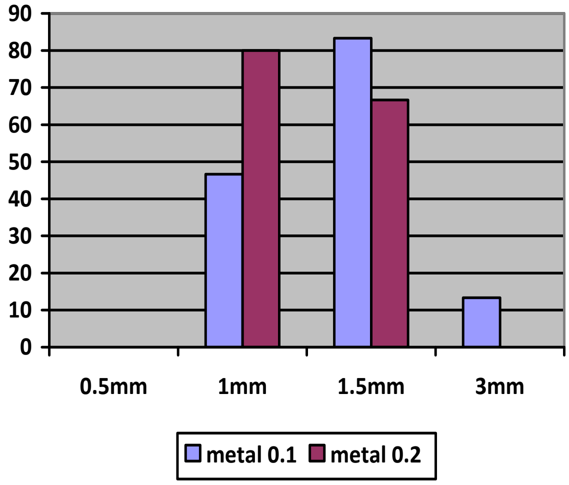

Figure 8: The results of the random rolls with the small die, depending on the thickness of the spacer (x-axis)

These experiments combined resulted in a total number of 3756 individual measurements.

Table 5: The number conducted to evaluate the quality of the results in the cases of random rolls and rolls on multiple antennas (the numbers apply to both cases)

Die	Combinations	Rolls
Large / Small each	30 rolls 2 metal foils 4 distances	240 per die
Milled-out	30 rolls	30
Total number of measurements taken:		**1020**

4.2 Results

We found that some combinations worked quite well, while others were extremely poor. Using multiple antennas consistently yielded bad results across all configurations. Also, placing our setup on a metallic surface significantly lowered detection rates – we were unable to repeat our initial performance gain from this setup. We will therefore focus on the results of random rolls with a single antenna, as well as on the position experiment (cf. Fig.7).

The best results – an average of 83.33% – were achieved using the small die with a metal foil of 0.1 mm and a 1.5 mm spacer (see Fig. 8). We obtained similar results for this die with a metal foil of 0.2 mm and spacer of 1 mm: 80% of the rolls were recognized correctly. Although certainly far from being feasible for real-world applications, we found this encouraging for an initial prototype.

Maybe more importantly, these two results disclose how crucial and delicate choosing an optimal configuration really is (see Tab. 6).

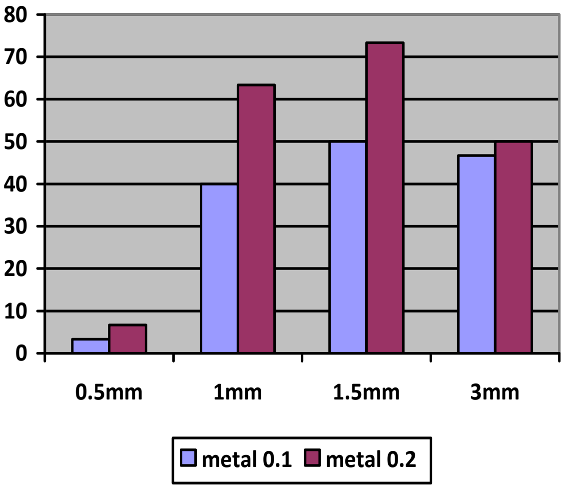

Figure 9: The results of the random rolls with the big die, depending on the thickness of the spacer (x-axis)

Starting with 1.5 mm and 0.2 mm, we get 66.67% success rate. Decreasing either the metal foil thickness or the distance, we receive better rates in both cases. Decreasing both simultaneously, however, yields an even worse rate. Note that we are talking about variation in the range of millimeters and less!

Table 6: The success rates of the small die depending on different thicknesses of the metal foils and spacers

		Metal Foil	
		0.1mm	**0.2mm**
Spacer	**1.0mm**	46.67%	80%
	1.5mm	83.33%	66.67%

In the case of the big die, the best recognition rate was 73.33%, using the 0.2 mm metal foil and a 1.5 mm spacer. However, unlike with the small die, the results were generally much better with the thicker metal foil (see Fig. 9). Using the milled out die with the 0.2 mm metal foil, we received a detection rate of 76.66% (see Fig. 10), more or less similar to the best recognition rate of the big die.

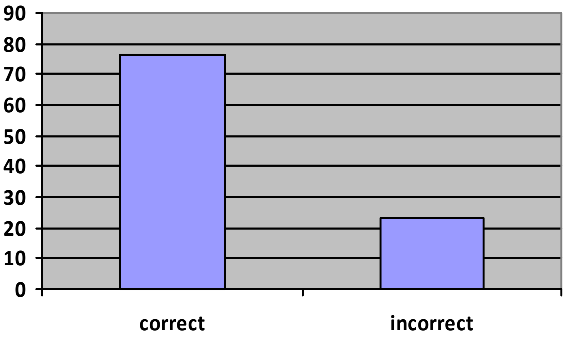

Figure 10: The results of the random rolls with the milled out die with the 0.2mm metal foil.

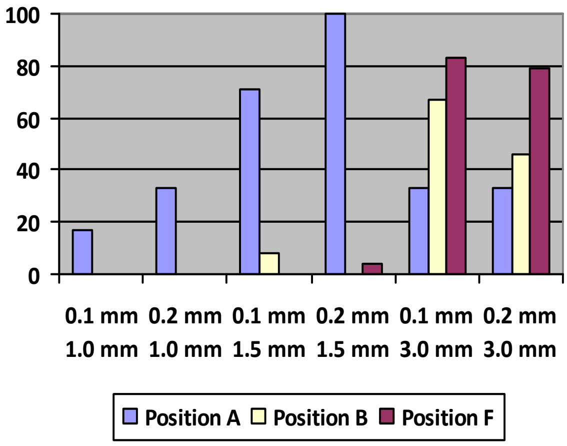

Figure 11: Results of the positions A, B and F (cf. Fig. 7), tested with the big die. The x-axis lists the thickness of the metal foil (upper row) and the thickness of the spacer (lower row), e.g., the first bar on the left reflects the results with 0.1mm metal foil and 1.0mm spacer

Finally, we will discuss the results of the position testing with all three dice. Fig. 11 displays the recognition rate depending on die configuration and position. We only give the results for positions A, B, and F, since all others had extremely poor recognition rates (e.g., below 5%). Fig. 11 shows that at the edge of the antenna (positions B and F), we only achieved reasonable detection rates with the thickest (i.e., 3.0 mm) spacer. Placing the die squarely at the center (i.e., position A), however, yielded very promising results. Using the big die with a 0.2/1.5 mm configuration, we even got a recognition rate of 100%.

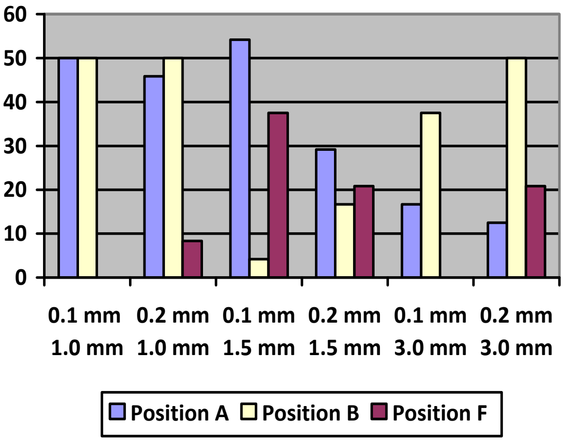

Figure 12: Results of the positions A, B and F (cf. Fig. 7) using the small die. The x-axis lists the thickness of the metal foil (upper row) and the thickness of the spacer (lower row), e.g., the first bar on the left reflects the results with 0.1mm metal foil and 1.0mm spacer

Though this value represents the perfect success rate, the practical utilization is somewhat limited, since regular dice rolls hardly land square in the center of an antenna. Nonetheless, at least we can conclude that a perfect recognition is theoretically possible.

The same experiment conducted with the small die generated less satisfying results. The best rates were about 50%. In contrast to the big die, however, these results were more evenly distributed (see Fig. 12). Fig. 13 shows the results with the milled out die. In contrast to the small and the big die, the center position did not produce the best results: while position A yielded a recognition rate of approx. 40%, the edge positions C and F received much better rates, 75% and 100%, respectively.

Summarizing these results, we come to two conclusions: first, our initial tests showed that, at least in principle, it is possible to construct a die that whose usage is feasible for real gaming applications. As pointed out before, the devil, however, is in the detail. This leads us to the second conclusions regarding the tests: the problem evidently is to find the optimal configuration for the given RFID environment.

5 CONCLUSIONS

In this paper we introduced augmented dice, traditional dice equipped with RFID technology to automatically determine the result of one or more rolled dice. We presented three die prototypes and discussed the results of a set of experiments for assessing the feasibility of our approach.

Our results lead us to believe that it is, in principle, possible to use RFID technology for constructing dice that allow us to automatically determine the rolled result. However, the devil is in the detail: as with all RFID applications, the success rate depends on several factors that can even influence each other. As far as the hardware components are concerned, the employed RFID technology (mainly low and high frequency systems, as ultra high frequency and microwave are not suitable in this case), the size of the antenna, and the size of the tags are the most critical factors. Additionally, special attention must be paid to the thickness of the metal foil. All these factors combined render the construction of an RFID based dice a very complex and difficult task.

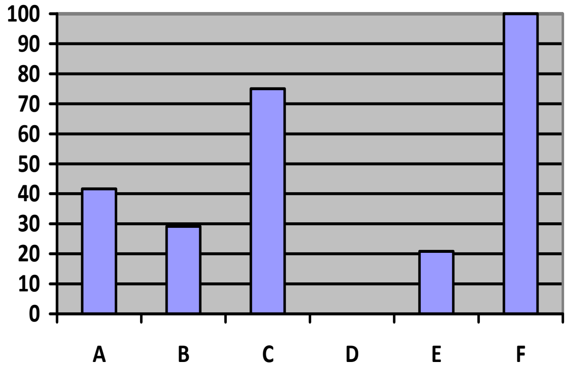

Figure 13: Results of all positions (x-axis), tested with the milled out die.

While our initial prototypes managed to reach a respectable 83% detection rate, this is far from being feasible enough for real-world applications. Successive prototypes will hopefully allow us to achieve an almost 100% detection rate. In particular, we are planning to focus on further decreasing the die size, possibly to 1x1 cm, and on improving the homogeneity of the RF field in order to enlarge the antenna's center area (which featured the best detection rates).

Alternatively, we might want to reverse our approach altogether. Obviously, one of the major problems we encountered was finding the best combination of metal foil thickness and distance to the tags. Thus, instead of trying to shield all tags except for the bottom one, we could try to shield *only* the tag at the bottom. This could be done with a liquid metal (e.g. quicksilver) inside the die, which would flow to the bottom after a roll, thus covering the bottom tag and preventing it from being read. However, using liquid inside the die will most likely influence the roll itself, besides raising serious health concerns. Alternatives to a metallic liquid would be small metallic marbles or even finer metallic dust. Last not least, one could construct a very lightweight, metallic inner cube that would come to rest on the bottom tag, thus disabling it.

Even if we are able to achieve an almost 100% detection rate, we will most likely require carefully tuned components (antennas, dice) that might be sensitive to various external factors (e.g., nearby liquid containers such as beer bottles or soda cans). However, compared to other technologies, the usage of RFID seems to promise an unobtrusive detection of the rolled result, and thus an undisturbed game flow and enjoyment, as this approach does not require an extensive setup such as tripod-mounted video cameras. If we are able to construct an even smaller version of our dice, e.g., 1x1 cm in size, we could close the gap between the real and virtual worlds in a truly pervasive and unobtrusive way.

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REFERENCES

1. Eriksson, D., Peitz, J., Björk, S.: "Enhancing Board Games with Electronics", 2005
2. Floerkemeier, C. and Mattern, F.: "Smart Playing Cards - Enhancing the Gaming Experience with RFID", Proceedings of the Third International Workshop on Pervasive Gaming Applications - PerGames 2006 at Pervasive 2006. Dublin, Ireland, May, 2006
3. Ishii, H. and Ullmer, B., "Tangible Bits: Towards Seamless Interfaces between People, Bits and Atoms," Proceedings of Conference on Human Factors in

Computing Systems (CHI '97), ACM, Atlanta, March 1997, pp 234-241

4. Magerkurth, C., Engelke, T., Röcker, C.: "The Smart Dice Cup: A Radio Controlled Sentient Interaction Device", Proceedings of 5th International Conference on Entertainment Computing, Cambridge, United Kingdom, 2006
5. Peitz, J., Björk, S. & Jäppinen, A.: “Wizard's Apprentice - gameplay-oriented design of a computer-augmented board game”, Proceedings of Advancements in Computer Entertainment (ACE), USA, 2006.
6. Rekimoto, J., and Sciammarella, E.: "ToolStone: effective use of the physical manipulation vocabularies of input devices", Proceedings of UIST’00, 2000, pp 109-117
7. Terrenghi, L., Kranz, M., Holleis, P., and Schmidt, A.: „A Cube to Learn: a Tangible User Interface for the Design of a Learning Appliance”, In: Personal and Ubiquitous Computing, November 2005
8. Ullmer, B. and Ishii, H., “Emerging frameworks for Tangible User Interfaces”, Carroll, J.M. (ed): Human-Computer Interaction in the New Millennium, Addison-Wesley, New York, 2001, pp 579-601