Designing a Competition for Autonomous Robots with a Restricted Set of Sensors with a Case Study of LEGO NXT

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Wojciech Marian Czarnecki, Krzysztof Szarzyński, Andrzej Wójtowicz

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Abstract:

Arrangements for a competition are not only difficult in terms of logistics of the event, but also require an assurance of quality. In this paper we analyze limitations which arise from design of the contest for robots equipped with a very poor sensor set. This issue is faintly explored – up to now research work usually has focused on results of a certain task and in addition it assumed almost having a free hand with a choice of components. The discussed question is significant on the grounds of primary principles: objectivity in grading, equal opportunities among participants and preservation of attractiveness of the tournament at the same time.

All of our actions have been evaluated through several years of existence of the PozRobot robotics contest. Over a three-year period we had an opportunity to test our approach on nearly 50 teams and almost 150 contestants from many Polish universities.

We analyze various aspects of performing the tournament and we indicate solutions to common problems, e.g. we touch upon dealing with an arena and objects which are placed on it. In particular, we propose a list of features which a well-designed competition should fulfill. To show our experience we describe an instance of a model competition. We outline new directions of further development of the contest, which are connected with a structure of the arena and possible changes in the limited set of the sensors.

Keywords: *robotics, competition, LEGO, NXT*

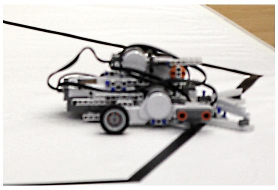
1. Introduction

The best way to put theory into practice is to introduce a challenge. This way we motivate students to use their creativity, learn [7,8] and improve their technical and social skills [6].

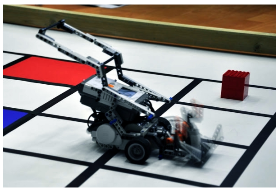
Robot construction is expensive, quite complicated and most of the robots are very specialized. That is why majority of the robotic tournaments are based on similar competitions like Sumo or Soccer [5]. The competitors face with a difficult task of constructing the best robot for each competition and when they decide on a project, it can be very hard to change its parameters.

Many students do not have any access to robotic laboratories equipped enough to construct specialized robots. One of the solutions to this problem is to restrict the competition to an easily modifiable, cheap and uniform robotic platform. This way every team can experiment with the shape and the construction of their competition robot.

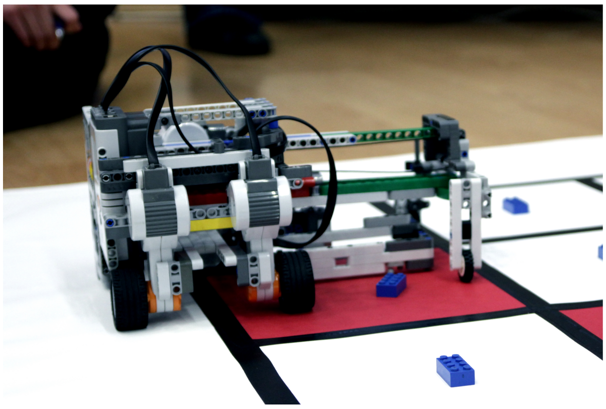
Our core assumption was to design a competition with very diverse tasks. This implies contestants' focus on advanced artificial intelligence methods rather than construction (see Fig. 1).



(a)



(b)



(c)

Fig. 1. Designed competitions for different artificial intelligence problems: (a) self-localization in unknown environment, (b) object detection and optimal planning, (c) optical character recognition

2. Programmable robotics kit

LEGO Mindstorms NXT is a good example of affordable robot construction kit. First of all, LEGO blocks give almost unlimited potential in creating versatile, mobile robots and the NXT Intelligent Brick provides sufficient computing power. Secondly, NXT comes with a variety of sensors. In context of our competition, the biggest advantage of NXT over other robotic platform (e.g. Arduino) is its standardized modularity which entails cost-free modifications of its construction.

The NXT system is currently available in two versions, both are similar and come equipped with:

- 3 servo motors with an odometer;

- 2 touch sensors;
- 1 light/color sensor;
- 1 ultrasonic distance sensor.

The NXT 1.0 version is equipped with a simple light sensor (returning the ambient or reflected light level), and the 2.0 version comes with a color sensor instead (which is able to measure amount of ambient or reflected light and recognize up to six basic colors). All of the sensors are compatible with both bricks. NXT uses a RJ-11 connector to connect the motors and sensors which are compatible with I^2C interface.

Many manufacturers provide auxiliary sensors and devices which can be used with the NXT brick. Most of them outperform the basic kit sensors in precision. Our goal was to create equal chances for all contestants, so we decided to limit the competitions only to the basic sensors manufactured by LEGO and included in the NXT kit. In the context of mechanical parts we allow use of any LEGO parts.

Restriction to only NXT robots with the basic set of sensors presents a big problem in designing the competition. Sometimes the very same limits motivate the participants to create very ingenious robots and this "atmosphere" makes the tournament interesting and enjoyable.

2.1. Motors and sensors

Basic NXT components are very simple and have some limitations. When the participants use them they have to take those constraints into consideration. Based on our experience we describe some characteristics of four mostly used devices:

1) The simplest, yet the most precise, is the binary **touch sensor**. It has a single button placed at the tip of a standard Lego NXT sensor casing. The button is small, so the contestants usually build some kind of leverage mechanism to indirectly contact with the environment and maximize their chances of detecting an obstacle or an object.
2) All of the **servo motors** are equipped with an odometer. According to the manufacture the device can work with a 1° precision [3]. To increase torque or speed the participants use gears. Unfortunately, LEGO blocks are not usually well fitted and sometimes the robot looses a grip with a surface. This accounts into an increasing odometer error. The teams cope with this problem by usage of reorienting algorithms.
3) The most characteristic sensor is the **ultrasonic distance sensor**. Its shape stands out from the others. It uses a ultrasonic transmitter located in the right "eye" and a receiver in the left one. Ultrasonic waves are good in assessing a distance to objects from couple of centimeters up to 1 meter but the accuracy is related to the shape of the distant object. For example, a simple cube placed in front of the sensor can appear 10-20 cm further if the cube is placed at an angle, or in some cases even "disappear" (due to the ultrasonic waves bouncing off and not returning to the receiver). This requires some experience from the contestants when using this sensor.
4) The most used sensors in our competition are the **light and color sensors**. Because of small reliability of the ultrasonic sensor the participants use the light or color sensor for navigation. The color sensor returns more information about the environment than the light sensor, but when used properly they are very precise. The lighting conditions and proper calibration are crucial when using these sensors. Some of the contestants build a casing around the sensor to minimize the external light conditions influence.

3. PozRobot tournament

PozRobot[1] is an annual national robotics tournament held in Poznań and organized by Adam Mickiewicz University. The first edition in 2009 was directed at primary and middle school children. In 2010 a special category – *Student* was introduced. The main focus of the *Student* category is to advertise artificial intelligence and robotics among students from all over Poland. The competition designed for students are more complex and strongly rely on usage of multiple sensors and advanced algorithms. Throughout the years we gained experience in creating competitions and developed a set of basic rules.

3.1. Basic assumptions

When we design competitions we try to follow four assumptions:

1) Competitions should be as objective as possible, so that we could evaluate the team based on just one run per team.
2) The competition setup or arena must be easy to reproduce. The contest is open to participants from all over the country, the competitions changes every year, and we can not demand from the participants to incur high costs of participation.
3) Competition design should blur the differences between the NXT 1.0 and NXT 2.0 sets. The color sensor from NXT 2.0 is much more accurate than the light sensor from NXT 1.0 and gives a big advantage to the teams which use it.
4) The tasks should maximally encourage usage of data gathered from the sensors and complex artificial intelligence methods.

The process of creating a competition for robots with a restricted set of sensors can be divided into four main elements:

1) an arena that is suited for their sensors;
2) objects which the robot is able to recognize;
3) character of the contest, a choice between tasks for a single or multiple agents;
4) a method of communication with the judges.

Each of these elements will be discussed in next sections. We will show the best solutions based on our experience from previous years.

3.2. Arenas

The environment which robots explore is the key element in every competition. Its form and quality decides the final result of a run of a robot and distinguishes between actual skills and pure luck. In classic robotics tournament this issue is not as crucial – robots can be equipped with any type of sensors, including cameras, laser range finders etc. In this case the robots can approximate their position in virtually any environment (a good example is the contest DARPA Urban Challenge [2]).

What kind of restrictions does a usage of a single light/color sensor, ultrasonic distance sensor or two touch sensors give? Because of large odometry errors (due to the precision of LEGO servo motors and the robot construction made from LEGO bricks not specially designed metal parts) it is necessary to add easily recognizable key points to the environment. In accordance with the sensor restrictions, the only reliable source of data is the light/color sensor, which suggests that the key points must be recognizable by it. To ensure constant data access those key points should be located on the ground.

We divide the arenas into two types: discrete and continuous. The discrete arenas are those wherein the key points locations allow to interpret the localization problem in context of a simple finite space. The best example, used frequently in PozRobot (and lately in other Polish NXT competitions or Istrobot [4]) is a matrix-type arena (see Fig. 2) which gives two major benefits. Firstly, it discretizes the problem by giving known in advance structure of N accessible fields. Secondly, the simple geometry provides easy methods of correcting the odometry errors exploiting a reorientation algorithm using the matrix lines (see Fig. 3). It is worth noticing that the usage of the single light/color sensor makes line following algorithms ineffective in this type of competitions, so the line geometry is the key factor in robots unambiguous positioning. Other interesting form of the arena with positioning support is an arena consisting of concentric circles, where the given method will set the robot perpendicular to the tangent of the circle (in the direction of the arena center).

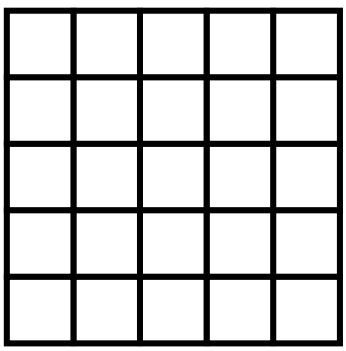


Fig. 2. An outlook on the matrix-type arena. Perpendicular lines help robots with self-localization

Second type are continuous arenas where the robots explore an environment with much less key points, usually limited by a thick black line and with no additional information on its surface. We experimented with this kind of setup in the previous years, but the results had clearly shown that this approach is wrong. The results in continuous competitions were very badly correlated with the final results of participants (see Table 1). Low correlation of such competitions like Marbles and Overtaking are consequence of direct interaction between robots which sometimes led to a jam. We draw a conclusion that continuous competitions are random. In addition the contestants were pointing that those competitions present a low objectivity level. Correlation in the last column of the table 1 is a Spearman correlation between scores of robots in some particular task and their final results after whole competition. One of the tasks – namely Bumper, was a very specific one, where construction of the arena was negligible so discrete/continuous distinction does not apply.

Tab. 1. PozRobot tasks comparison

name	agent	type of map	correlation
Bumper[a]	single	NA	0.85
OCR[b]	single	discrete	0.81
Map[c]	single	discrete	0.74
GPS[d]	single	continuous	0.54
Marbles[e]	multi	discrete	0.19
Overtaking[f]	multi	continuous	-0.12

[a] pursuit of a randomly moving object
[b] pattern recognition (see Section 4)
[c] detection positions of known landmarks
[d] self-localization problem
[e] competitive gathering of objects
[f] race of two robots

3.3. Objects

Second important matter of each competition are the objects that the robot must find, recognize, compare or transport. Again the key factor is to choose the objects, so that the restricted set of sensors allows to complete the task. Another impediment is the maximal number of servo motors connected to the NXT brick. Two of them must be used to movement of the robot – this leaves only one for manipulations of the objects and movement of sensors. So if the robot uses a light/color sensor to navigate (it is directed accurately down) it must rely on an auxiliary distance and touch sensors. The other possibility is that the robot uses the servo motor to change the position of the light/color sensor. In this case it is not hard to connect the sensor with some kind of a manipulator, but it is practically impossible to use it with a movable ultrasonic or a touch sensor.

Because of this problems the objects must differ at least in size, preferably the height. This feature is easy enough to recognize by all of the sensors and is independent of the robots position on the arena (the difference of heights between two objects on a 2D arena is maintained). The difference in a color of the objects is not a good feature. The main problem is maintaining

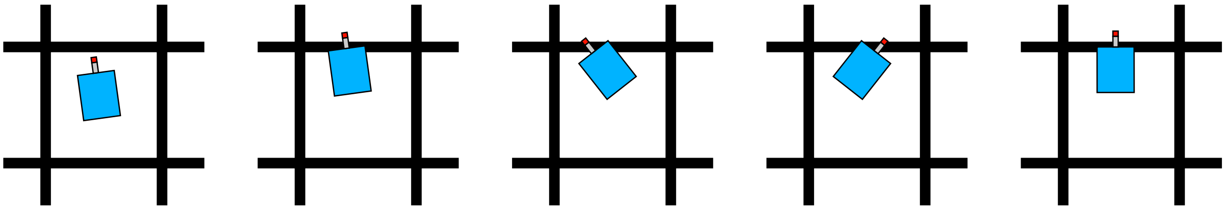


Fig. 3. The reorientation algorithm for the matrix-type arena. (a) Let us consider a robot (a dark-gray rectangle) which can turn in place, equipped with a light/color sensor (protruding pointer in the front) directed to a floor. Due to odometry errors it may happen that the robot is not in a desired position (perpendicular to a line). (b) The robot moves forward as long as its sensor overshoots the line. (c) Then it stops and turns left until the sensor detects the line. (d) Afterwards it turns right – again until the sensor detects the line, but this time the robot also counts motors rotation angle X. (e) Finally, the robot turns left by $\frac{X}{2}$ rotations and as a result it stays perpendicularly to the opposite line

a backward compatibility with NXT 1.0 sets that uses the light sensor. This sensor can reliably distinguish no more than three colors "on the ground" and two "in the air" (two colors of objects and one "ambient color" meaning the absence of the object).

We experimented with many different objects ranging from cardboard models, through bricks, up to balls and LEGO blocks constructions. Our experience shows that the best option is to use cuboids built from LEGO blocks. Their doubtless advantage is that they are standardized and the participants from all over the country can easily reproduce them. In addition their modularity allows forming different shapes (for example cuboids of different height).

We believe that the optimal solution is to use objects that can be distinguished by using the color or just by measuring their shapes. For example we propose cuboids build from LEGO blocks with given height and each construction is also built from different colored blocks. This way we give the participants two ways of recognizing the structures and also allow them to minimize errors by confronting the measurements from two different sensors. An alternative solution of the recognition problem is to encode information about an object directly onto the arena (for example by using a printed barcode in front of the object) but this will be the topic of our future experiments.

3.4. Competition

It is doubtless that robotics tournaments are more attractive that algorithmic competitions. And what could be more impressive than two robots fighting each other? Unfortunately, creating a competition in which two robots simultaneously perform their tasks and can physically interact with each other are not a good choice for NXT tournaments. The basic issue is the problem of detecting a collision with the other robot, especially when using the basic set of sensors.

We experimented with those types of competitions in the early editions of PozRobot. Definitely most of the "duels" wherein both robots had the opportunity of contact ended in some form of deadlock or pushing one of the robots randomly out of the arena (see Table 1). This leads to an obvious conclusion that we should not introduce competitions that create a risk of physical contact between the robots. The lack of direct competition increases the objectivity of scores. It is worth noticing that competitions with two competing robots also requires the usage of the tournament formula which prevents objective scoring of all runs.

3.5. Methods of communication

The last key element is the form of communication with the judges. Except the most obvious one – direct manipulation of objects on the arena, we have three more possibilities:

1) displaying the results on the robot's LCD;
2) emitting a sound signal;
3) communication using Bluetooth.

These three ways help to improve the competition, i.e. by independent scoring of its different parts. The robots task can be moving some physical objects across the arena but is additionally scored for collecting data about the environment. To verify the robots belief we use those mechanisms e.g. we require it to display the arena map on its LCD. The Bluetooth communication although giving the greatest opportunities used to be the most unreliable. It lead to unnecessary increase in complexity of the competition and to dependence from external factors. Because of this reason we stopped using this method of communication.

This way we can distinguish robots which successfully completed parts of the task from these who did not.

4. Exemplary competition

One of the most interesting competition played on PozRobot was "OCR". The arena was a 5×5 matrix where some of the fields were filled with a red color (pixels) and the rest was white (empty fields). The pixels were shaped to resemble a digit (see Fig. 4) unknown to the participants (but the same for all starting teams). There was no known finite set of symbols, only some basic rules were given to the participants. In the center of each field lied a single 2×4 pin LEGO brick. The task for robot was to collect and deliver to the starting point a number of blocks given by the encoded digit. As in each of the PozRobot competitions –

robots dimensions were limited to the 30 cm cube and had to be fully autonomous. It was also forbidden to alter the arena anyhow (except moving LEGO bricks).

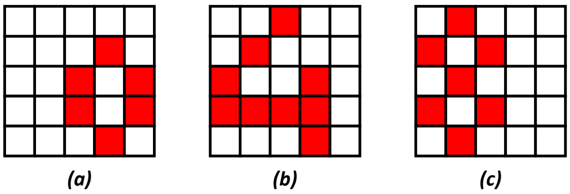


Fig. 4. Sample digits from OCR task. A size of a single pixel is 20 cm x 20 cm. Boundary lines have 2 cm width

The scoring was based on:

1) correct mapping of the map and displaying it on to the LCD;
2) minimizing the number of visited fields;
3) correct digit recognition;
4) delivering the correct amount of blocks;
5) time of completion.

This competition fulfilled all of the key assumptions given the type of robots:

1) The arena was discrete and allowed for easy navigation.
2) It was a single agent competition.
3) It was multilevel evaluated, minimizing the variance of the results.
4) It required maximal usage of rudimentary knowledge (in the context of a restricted set of sensors and in the fact that the highest score was achieved by minimizing the number of visited fields – which is an additional optimization factor).

One could observe many interesting ideas for completing OCR competition. Firstly, it is worth noticing that contestants used various artificial intelligence methods containing (but not limited to):

- A* algorithm for rapid path-finding to the most informative fields on the arena;
- K-NN supervised classifier for scanned digits recognition;
- Lightweight implementation of feed-forward neural network used for color recognition and for digits recognition.

Secondly, we could also observe very interesting constructions. The restricted set of sensors/actuators is not only the limitation – it also motivates creative thinking. One of the teams built robot with smaller bot inside, composed of one motor (for movement) and color sensor (for fields scanning), that was sent to distant parts of the arena while robot was just standing in one position (see Fig. 5). Contest rules stated that robot ”visits” some field if its main brick is placed above it – so this strategy maximized the amount of points gained for not visiting fields while still collecting all required information about the arena.

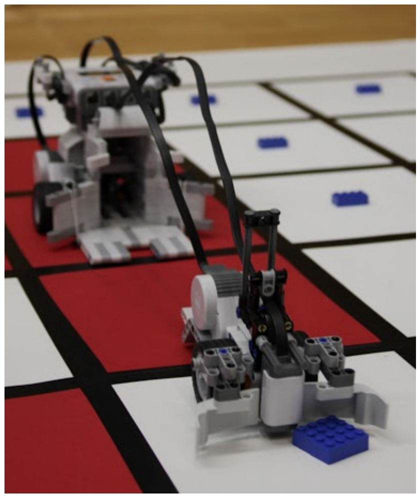


Fig. 5. One of the OCR robots containing smaller bot inside, used to scan distant arena fields

OCR was very well received by both contestants and viewers. Even though some teams did not score any points (or even got negative ones – see Table 2 for details), most of robots did quite well (low score was a result of e.g. exception thrown by the contestants code after their robot correctly mapped the whole arena). Task itself was a challenging problem that correctly distinguished between very good robots and average ones. We have also received positive response directly from the contestants. One of the Jagiellonian University teams referred to OCR as *the best designed competition for NXT robots*.

Tab. 2. OCR Scoreboard

team	points
Jagiellonian Team Karel 2.0	72.5
superkonfodopieszczaczoszybotron	40
Robomaniacs Prime	25
Who's NeXT?	25
Goffery z Dzemorem	23
bierzsiedogarow.pl 2	21
Aniolki Charliego	14
Jagiellonian Team Valentino 2.0	12
RoboWarriors	7
GRIK	5
Yet Another Robomaniacs Team	0
Garwutki	0
Robomaniacs Academy	0
ROBOLE	0
bierzsiedogarow.pl	-3

5. Possible development

Firstly, interaction between robots on the map, especially giving permission to fight, turns a competition to a spectacular show (e.g. Sumo). Naturally it is a tip of a hat to the audience but as we stated earlier this approach simply leads to a random results. Certain consensus might be so-called separated rivalry. As an example we can imagine a situation where robots are walled off and compete for some shared resources located in holes of the wall. This illusive permission raises attractiveness of the competition and ensures objectivity in scoring.

Secondly, in the course of time we may consider resignation from adjustment to the light sensor from NXT 1.0. This case looks similarly to the RCX – the first LEGO Mindstorms generation, which nowadays is used very rarely. Moreover, in 2013 LEGO plans release the third generation – EV3 [1], which may speed up a change in competitors' equipment. This could give us a chance to put into a map larger variety of points of interest.

Thirdly, we consider creation new kinds of map, despite of foregoing matrix and circle. Of course it should follow all mentioned earlier principles. The most promising area to explore are maps with some kind of knowledge encoded in barcodes and improved interactivity (as most of the currently considered arenas were fully static). This way one can augment the robots reality with arbitrary complex data. One such idea is to place (also NXT powered) non-player robots (NPR) on some of the matrix fields and use barcodes to inform competing robot about the action, that this NPR will perform if its touch sensor is hit. This would not only improve the attractiveness of competitions, but also would create a new abstraction layer for solving which sophisticated artificial intelligence algorithms would be required.

Last but not least – we want to open our competition for contestants from other European countries. Hopefully PozRobot 2014 will be our first International Robotics Competition for LEGO Mindstorms robots.

6. Conclusion

As a result of several years in organizing the PozRobot tournament we gained some experience in selection of appropriate tasks. The restricted set of the sensors ensures equal chances among competitors in terms of technology but present a great challenge to the organizers (in designing a competition which gives equal chances) and to contestants (who need to use creative thinking in overcoming the limitations of the restricted set of the sensors). It is beyond doubt that a choice of a discrete map helps with evaluation of a task and reduces problem of the imperfect sensors.

This year we organize together with Jagiellonian University the first edition of KrakRobot competition, based on the exact same concepts as PozRobot. These two contests will be alternating in following years. All this year's tasks are discrete, single agent, and using objects easily distinguishable by light sensor and touch/ultrasonic one.

We are interested in feedback from other organizers, especially with regard to fixing problems connected with continuous maps. We deeply believe that our collaborative effort will make robotic competitions much better in the future.

Notes

[1] http://pozrobot.pl

AUTHORS

Wojciech Marian Czarnecki – Adam Mickiewicz University in Poznań, Faculty of Mathematics and Computer Science, Umultowska 87, 61-614 Poznań, e-mail: w.czarnecki@amu.edu.pl, www: czarnecki.faculty.wmi.amu.edu.pl.

Krzysztof Szarzyński – Adam Mickiewicz University in Poznań, Faculty of Mathematics and Computer Science, Umultowska 87, 61-614 Poznań, e-mail: quati@amu.edu.pl, www: quati.faculty.wmi.amu.edu.pl.

Andrzej Wójtowicz* – Adam Mickiewicz University in Poznań, Faculty of Mathematics and Computer Science, Umultowska 87, 61-614 Poznań, e-mail: andre@amu.edu.pl, www: andre.faculty.wmi.amu.edu.pl.

*Corresponding author

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