AC 2011-67: RESOURCES FOR ROBOT COMPETITION SUCCESS: ASSESSING MATH USE IN GRADE-SCHOOL-LEVEL ENGINEERING DESIGN

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Abstract

This is an exploratory study of the use of math in the design solutions of a middle and elementary school level robot competition. Competition scores were used as measures of engineering design success. Sixteen teams were interviewed on the day of the competition to assess their use of math in their design solutions. Four of those teams were followed additionally prior to and after the competition using survey instruments measuring math use in robot transfer problems and attitudes toward robots and math. These measures assessed potential impacts beyond competition success. Only one quarter of the teams used math explicitly in their design solutions. The use of math was found to have a highly variable relationship with design success, with the highest and very low scoring teams in the competition having used math. However, both successful and unsuccessful cases of teams that used math did exhibit improved use of math on the transfer test. Further, in the case of an unsuccessful math-using team, the students' did have more positive interest in math and in robots as well as more positive views about the value of math for robots after the experience of preparing for and participating in the competition.

Introduction and Background

As robots have become cheaper over the past two decades, they have increasingly become an accessible way for K-12 students to learn about engineering design.[1] Simple robots provide a concrete form for younger students to explore issues related to structures, mechanisms, and behaviors through the design of the robots using building blocks, motors, sensors, and programmable bricks.[2]

Increasingly a common context for learning with robots has been in robot competitions.[3] A primary goal of these competitions is to build students' interests in engineering, but also their skills in engineering as well. Especially in robot competition settings that aren't specifically tied to a formal course, the theory is that students will be motivated to test and learn about more general ideas by building a robot to successfully perform a specific task.[4] But prior research in such settings has often relied on self-reports by students and coaches only after the experience has concluded to assess what gains in skills and content as well as what changes in interest and attitudes resulted from participation.[5, 6] This leaves open many questions about what is the substance of such learning, what is the relationship between success in the competition and changes in learning or attitudes, and what sorts of approaches by participants may affect this relationship.

Prior research on a high school robot competition identified a teams' use of mathematics in their solution process as a predictor of competition success.[7] This aligns well with undergraduate level[8], graduate level[9], and authentic engineering design[10] in which mathematics is a key element. It not as clear whether math use in design by elementary and middle school students would be similarly productive. By analyzing the design solutions of competition participants in detail, understanding what opportunities to use math in their design solutions were available, and investigating the types of design solutions that were more successful in the competition, we might better understand the process by which robotics can indeed lead to positive outcomes.

The Robot Competition

Every year, thousands of adults around the world serve as coaches and mentors for teams of elementary and middle school students in increasingly popular robotics competitions such as FIRST® LEGO® League (FLL). Typical grade-school-level competitions like FLL involve the building and programming of small robots to solve a specific design challenge using robot platforms such as the LEGO MINDSTORMS NXT. A challenge usually consists of a series of missions that involve pushing, retrieving, picking up, and placing objects. Each mission is designated a point value and the object is to earn as many points as possible in a limited time, usually a few minutes. The challenges vary from competition to competition and change every year, but teams are generally given months to design their solutions.

The focus of the present study was a small, local-level robot competition that was modeled after a typical robotics competition. This competition, called "May Madness", was sponsored by a nationally recognized robotics education organization that also hosts the annual state FLL championship. This robot challenge was called "Botball Hybrid II", and like FLL competitions, it was to be completed with LEGO MINDSTORMS NXT robots and was geared toward elementary and middle school age students.

Figure 1: Botball Hybrid II Robot Competition Challenge Game Board

Although not quite as complex as typical FLL challenges in terms of the number of missions or the variety of objects on the board, the Botball Hybrid II challenge includes a number of elements that require sophisticated solutions (see Figure 1). Two teams occupy the board at the same time, a black team and a white team. Each team can have one robot on the board at a time and the teams start at opposite ends of the board. The object is to get the most points possible in a 90-second round. Points are obtained by collecting ping-pong balls and toilet paper tubes of the team's color and also common nests and foam balls. Knocking the ping-pong balls loose gets some points, but the most points are obtained by bringing the objects back to a team's end zone. Even more points are obtained by lifting the objects into the gutters on the side of the table.

Research Questions and Hypotheses

The focus of the present study was to investigate ways that incorporating math in their competition design solutions may have deepened students' experiences with robots. To this end, this study had the following research questions:

1. Are there opportunities to use math in this typical grade-school-level robot competition challenge?

2. Does using math have any impact on a team's competition success?

3. Are there benefits to using math in any other sense, such as in changes in robot problem solving or attitudes about robots?

K-12 students are often not fluent in mathematics and so using math in their design process may hinder their design success. Further, the nature of the competition tasks may not reward math use. We hypothesize that such barriers to math use do indeed exist and that they contribute to many teams choosing not to use math in their solutions. However, we hypothesize also that teams choosing to use math in spite of these barriers can exhibit positive benefits from doing so, both in terms of design performance in the competition challenge itself, but also in terms of learning and more positive attitudes about robots.

Method

Participants

Of the 22 total teams participating in the competition, 16 teams consented to participate in the study. Included were 9 middle school age teams and 7 elementary school age teams. Although most teams consisted of students in a mix of grade levels, the oldest team was made up of all eighth graders and the youngest team was made up of all second graders, so there was a fairly large range in grade levels. On average there were 7 students per team ($SD = 3$), with one team made up of a single student and three teams with the maximum of ten students.

Of the 16 teams in the study, 4 teams consented to participate as *Focus Teams*. The *Focus Teams* were observed in greater depth prior to and after completion of the competition. Two of these *Focus Teams* were composed of middle school aged students and two of elementary school aged students.

Materials

Two survey instruments were used to measure students' ability to use math in robot transfer problems and their attitudes toward robots and math. These measures assessed whether a team's participation in the competition, including whether they used math in their process, was related to outcomes beyond competition success. The *Robot Math Survey* was adapted from validated assessments of problem solving using proportional reasoning.[11, 12] Items from those assessments were modified to focus on robot motion problems. The *Robot Math Survey* (Appendix A) consisted of 12 multiple-choice and short-answer questions that asked the students to solve problems involving robot motion (overall Cronbach's alpha = 0.82).

The *Robot Attitude Survey* was adapted from a validated inventory of attitudes toward mathematics.[13] Items from that inventory were modified to focus on robotics and the relationship between mathematics and robotics. The *Robot Attitude Survey* (Appendix B) consisted of 13 five-point Likert-scale items (overall Cronbach's alpha = 0.88) that measured students' attitudes on three subscales: their level of interest in robots (Cronbach's alpha = 0.82), their level of interest in mathematics (Cronbach's alpha = 0.81), and their view of how valuable math is for doing robotics (Cronbach's alpha = 0.73). The internal reliability measures reported for both the *Robot Math Survey* and the *Robot Attitude Survey* were calculated on the present data, but we have observed similar levels of internal reliability for similar age groups on these same measures in our other, related work in which we are also investigating math in robotics.[14, 15]

The *Design Strategy Questionnaire* (Appendix C) was created to gather descriptive team information and to assess the type of design strategy they used. It was a structured interview conducted by a researcher and included two parts. In the first part, the team's coach was interviewed about the number of students and adults on their team, their grade and experience levels, and the number of hours that the team met in preparation for the competition event. In the second part, one or two students from the team were asked to describe their designed solutions to the challenge and how they came up with those solutions.

Study Design

The final rank in the competition was used as the dependent measure of engineering design success. Each team participated in three rounds, and their highest score of those three rounds was used to determine their final ranking in the competition. Other outcome measures included the change in robot problem solving or in attitudes as measured by the two surveys, although these data were only available for a subset of the teams included in the study. The primary independent measure included the type of strategy that the team used in the design solution. Interviews assessed whether teams used math in their design solutions.

Procedure

The *Robot Math Survey* and *Robot Attitude Survey* were administered to the students on the *Focus Teams* soon after the competition scenario was released to provide an assessment prior to the majority of the teams' preparation activities. The competition scenario was released 9 weeks prior to the competition event and all of the *Focus Teams* were surveyed within 4 weeks of that time. The surveys were administered at each team's normal meeting location. Students were

given 25 minutes for the *Robot Math Survey* and 5 minutes for the *Robot Attitude Survey*, one immediately following the other. They completed both surveys individually. On the *Robot Math Survey* they were instructed to give an answer for every question, to show their work, and were permitted to use a calculator. On the day of the competition, researchers interviewed all of the teams participating in the study using the *Design Strategy Questionnaire*. Finally, in the weeks immediately following the competition, the *Robot Math Survey* and *Robot Attitude Survey* were administered a second time to the students on the *Focus Teams*. The surveys were unchanged from the previous administration, they were administered again at each team's normal meeting location, and the procedure was identical.

Results

The Range of Strategies

The Different Strategies

The teams came up with a range of qualitatively different solutions, both across teams and within teams in terms of solving different missions within the overall challenge. However, every design strategy included at least one common component—moving the robot to the center of the board to begin scoring points. We focused on the design strategy for this component to compare across teams. Table 1 a list and description of the different strategies that teams used, and the number of teams that used each approach.

That only 3 teams used a (non-rotation) *Sensor-Based* strategy is likely a direct consequence of the nature of the particular robot challenge. In particular, the toilet paper tubes were not steady enough for a robot's touch sensor to contact them without tipping the tubes over. As a result, teams seeking to score using the tubes had to choose non-contact means of controlling their robot's movement. The 3 teams that did use a *Sensor-Based* strategy on their first move were all going for the nests, which are much heavier than the toilet paper tubes. However, for various reasons, even these teams abandoned use of their sensors in their moves later in the challenge. In addition, the board surface featured few marked lines, making line-following and line-tracking less attractive.

The remaining 13 teams programmed their initial move using the rotation sensor, effectively moving a set distance forward. However, those 13 teams used qualitatively different methods to choose their motor rotation values, especially the initial value. Some teams guessed; others used the view mode; but 4 teams chose to start with a math-based prediction based on a measurement of the desire robot movement. Although certainly not a majority of teams, 25% of the teams interviewed did use mathematics explicitly in their design solution in this way.

A Math-Based Strategy for Calculating Motor Rotations

Students making math-based predictions used several different mathematical relationships to arrive at their predictions. For example, one group measured how far the robot moved forward with each motor rotation, and then calculated how many of those 1-motor-rotation distances the robot needed to move the total distance to the target. The students then entered this value into their program, tested it, and fine-tuned the value to get the robot to exactly the right spot. One notable quality of this strategy is that it is not purely mathematical – all 4 teams that used

Calculate-Test-Adjust for their initial motor rotations value ended up having to refine their value with guessing or with the view mode afterward. A math-based measurement and prediction does not appear to be sufficient on its own for this type of competition challenge.

Table 1: Strategies Observed for the Robot's Initial Movement

Strategy	# Teams	Description
Guess-Test-Adjust	6	Students guess an initial value for the motor rotations, try it out on the robot, and then adjust the value to be bigger or smaller based on whether the robot went too far or not far enough. It is often not clear how students arrived at their initial guess. Teams who used this strategy also differed in how they made the adjustments: some used a systematic strategy in which they went up by whole numbers first, then smaller numbers, while others used more arbitrary adjustments.
Calculate-Test-Adjust	4	The only strategy that was explicitly math-based. Students measure the distance the robot has to move. They then make a mathematical prediction about the correct rotation value for the movement based on the size of the robot's wheels or a known distance the robot moves in one rotation. All of the teams who made their initial calculation this way had to fine-tune that value afterwards using adjustments that resemble the *Guess-Test-Adjust* strategy or the *View-Mode* strategy.
View-Mode	3	Students use the view mode on the NXT and then "walk" their robot (push it by hand as the wheels roll along the ground) to the desired destination. They read the value displayed and use that value in their program. This strategy is described in the NXT User Guide pp. 31-32.
Sensor-Based	3	The only strategy in which the robot does not travel a set number of wheel rotations (or duration of time). Students program the robot to move until a physical sensor stimulus provides a cue to stop. For example, running forward until the robot bumps into a nest and a Touch Sensor is triggered.

The Relative Success of the Different Strategies

The ranks of the teams who used each strategy were compared to assess the extent to which each strategy was related to design success. Figure 2 shows the distribution of ranks in the competition of the teams who used each strategy. Looking at the mean ranks, the *View-Mode* strategy was on average the most effective and the *Sensor-Based* strategy was on average the least effective, and this particular contrast was statistically significant ($t(4) = 4.98$, $p = 0.01$). The *Guess-Test-Adjust* and the *Calculate-Test-Adjust* strategies are in the middle and similar to each other. As stated above, it may have been that this particular challenge was somewhat biased against the use of sensors, and so it is not surprising that teams who used the *Sensor-Based* strategy did not perform well.

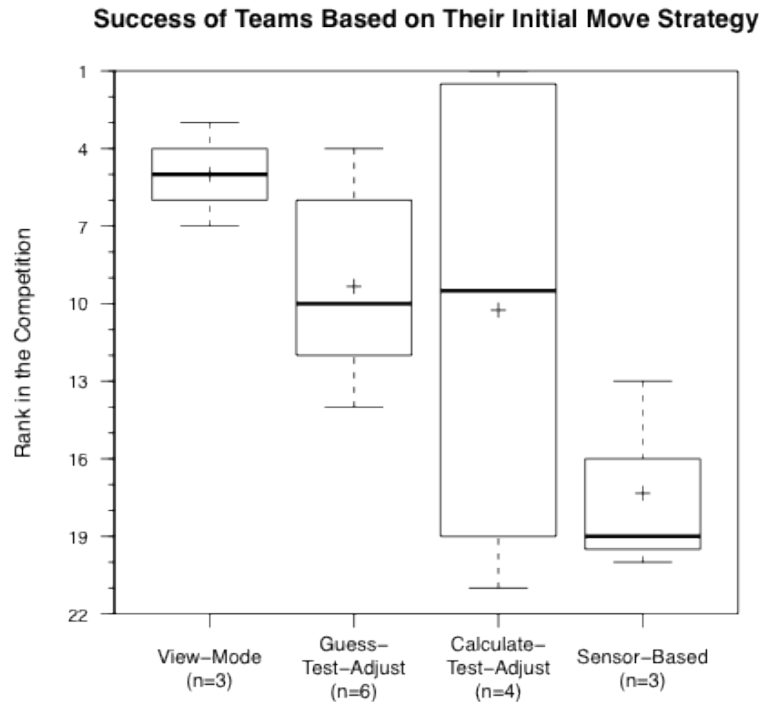**Success of Teams Based on Their Initial Move Strategy**

Figure 2: Box plots [high/low, interquartile range, median (bold bar), and mean (cross)] of Team Rank in the Competition Based on the Initial Move Strategy

The teams using the *View-Mode* strategy did perform particularly well. We hypothesize that this strategy may lead to success for two reasons. First, teams that use this strategy can program their movements quickly. Figuring out the correct motor rotations value is straightforward and fast, so that frees the team up to spend their limited time improving other parts of their solution (e.g., making their robot base solid and their attachments functional). Second, the *View-Mode* strategy is very reliable, so once teams get a motor rotation value by using this strategy, they then have a lot of confidence that that value is the right one and will work well. In essence, the *View-Mode* strategy is easy to implement quickly and gives very reliable results, which explains why teams who chose that strategy tended to do well in the competition and there was very little variance among them.

The Success of the Math-Based Strategy

Compared to rolling the robot on the ground and reading a number, both *Guess-Test-Adjust* and *Calculate-Test-Adjust* are slow to implement and potentially less reliable as well. Again inspecting Figure 2, on average teams who used these strategies performed at an average level in the competition, and not as well as teams who used the *View-Mode* strategy. Alternatively however, when inspecting the variation within strategies, the *View-Mode* strategy was the least variable, but the *Calculate-Test-Adjust* strategy has a large variability spanning almost the entire range of possible ranks.

A closer look at the 4 teams that used the *Calculate-Test-Adjust* strategy shows that two of them were the top ranked teams in the entire competition (ranked #1 and #2 out of 22 teams). This

suggests that using a math-based measure-and-predict strategy can be very powerful. At the same time, the other two *Calculate-Test-Adjust* teams were ranked #17 and #21—the complete opposite end of the spectrum in terms of design success.

This bi-modal distribution for the *Calculate-Test-Adjust* strategy suggests that for this strategy in particular, it may be important to assess how the strategy was used. We hypothesize that when the *Calculate-Test-Adjust* strategy is implemented well, it is just as quick and just as reliable as the *View-Mode* strategy, if not even better. Done without a full understanding, however, the calculations could involve considerable time and cognitive resources that distract from committing those resources to other parts of the design solution.

In sum, a plausible explanation is that teams who are fluent with mathematics can use math-based measurements and predictions to their advantage by determining the correct motor rotation values for different moves relatively quickly. As with the *View-Mode* strategy, this timesaving frees resources for use on building tasks and fine-tuning overall strategy. Teams that are less fluent in mathematics, however, may take longer to perform the math-based calculations, and make more errors, thus taking time away from working on other important parts of the task.

A Case Study of the Winning Team

So what was it that the most successful teams did that led to their success? By chance, one of the teams that we followed in greater depth as a *Focus Team* was the winning team for the competition. To setup the case study of this team, we first describe the *Focus Teams* more generally.

Descriptive Information on the Focus Teams

Two of the *Focus Teams* consisted of students from elementary grades—referred to here as Team E1 and Team E2. The other two consisted of middle school age students, and are identified as Team M1 and Team M2. Table 2 shows the information collected on each team from the *Design Strategy Questionnaire*, including their grade levels, the number of students on their team, and the strategy the team used for their first move. Also included in the table is each team's rank and best score from the competition.

Perhaps not surprisingly, the middle school age *Focus Teams* outperformed the elementary school age *Focus Teams* in the competition as evidenced by their much better ranks and final scores. This is not a universal effect, however, as there were a number of elementary school age teams who did do very well in the competition (ranked #5, #7, #9, & #12). Within the *Focus Teams*, two teams (Teams E2 & M2) used the math-based *Calculate-Test-Adjust* strategy for their first move, and the other two teams (Teams E1 & M1) used a non-math-based strategy. This comparison provides additional qualitative data on the effect of using math in a team's solution. And of the two *Focus Teams* that did use mathematics explicitly in their design strategy, one team didn't do so effectively (Team E2), and the other (Team M2) did, obtaining the highest score overall in the competition. Analyzing Team M2's approach in more detail may provide some insight as to the nature of effective mathematics use in design solutions for these robot competitions.

Table 2: Features of the Focus Teams

Team	n	Students Experience Level	Students Grade Level	n	Coaches/Mentors Experience Level	Setting	Hours	First Move Solution Strategy	Final Rank	Best Score
E1	1	2+ prior competitions	Elementary 1 – 5th	1	Rookie (no STEM-related experience)	Individual	30	*Sensor-Based*	20	9
E2	7	Rookies	Elementary 3 – 5th 2 – 4th 1 – 3rd 1 – 2nd	2	Rookie (home school teacher) Rookie (retired programmer)	Neighborhood /families	20	*Calculate-Test-Adjust*	17	14
M1	10	2 – Rookies 4 – 1 prior competition 4 – 2+ prior competitions	Middle 7 – 8th 3 – 7th	1	2+ prior competitions (math, science, and robotics teacher)	School	50	*Guess-Test-Adjust*	6	51
M2	10	6 – Rookies 4 – 2+ prior competitions	Middle 1 – 8th 6 – 7th 3 – 6th	1	2+ prior competitions (gifted and math teacher)	School	17	*Calculate-Test-Adjust*	1	91

A Case Study of Team M2

Team M2 was a school-based team consisting of 10 students, all from a gifted program in a suburban school. There were one 8th grader, six 7th graders, and three 6th graders. Four of the students had been to a competition before, but the rest were rookies. Their coach—the teacher for the school's gifted program—had been a coach for five previous robot competitions, so she was very experienced. They reported spending about 17 total hours preparing for the competition, with about 10 of those hours in just the last two weeks. This was, in fact, on the low end of total preparation time compared to other teams that were interviewed.

Team M2 was large enough and had multiple robots, and so was able to split into two sub-teams. They divided the responsibilities of their sub-teams by missions, with one sub-team working on the toilet paper tubes and the other sub-team working on the nests. These robots as a whole were not very complex, but each robot design and attachment was well tuned to specific parts of the challenge.

Team M2 ended up with a high score in the competition of 91 points. The team recorded a video of their winning round and shared it with us for this study. Inspecting the video of Team M2's robots in action, it is clear that all of their movements are quick and reliable. They retrieve all three toilet paper tubes very fast and without any fumbling, possibly because Team M2 was able to use the *Calculate-Test-Adjust* strategy to make efficient calculations that got them close to correct motor rotation values very quickly. The timesaving allowed them to work on other aspects of the challenge, such as ensuring that both of their robot designs were robust and reliable. This too, shows clearly in their winning round, as Team M2 uses both of their robots effectively and reliably, each on their own mission.

Other Math Used by Team M2

Team M2 did use *Calculate-Test-Adjust*, a math-based strategy for movement, but in addition to this, they used mathematical thinking in an entirely different way than simply focused on determining the correct robot movements. One of the students on Team M2 did a systematic analysis of the points that the team could earn based on observations of their practice rounds. She measured the time they took to complete each mission and the points that they could get, and then identified the best ordering to help maximize their total points. She determined that their team could get the toilet paper tubes (and all 9 ping pong balls contained within them) back to base then deposit the balls into the gutter and the tubes into the end zone in 52 seconds for a total of 57 points. Then they would still have time to pursue the nests for additional points. In their winning round, they execute this strategy almost without error, although a later mission ends up knocking one of their toilet paper tubes from the end zone scoring area.

Although the team no longer had documentation of their analysis when interviewers met with them after the competition, we have recreated the underlying analysis in Table 3. When the points are broken down in this way, what becomes salient is that the large majority of points are to be gained by going after the ping pong balls (90 points out of a max of 145 points), half of which are in the toilet paper tubes, and putting the ping pong balls in the gutter. And this is exactly what Team M2 did, doing so very efficiently and reliably. Thus, Team M2's use of

mathematics extended beyond programming into the planning process itself, and appears to have been an integral part of their competition success.

Table 3: Points Breakdown Analysis for Maximum Possible Score and Team M2's Winning Round (bold values are summed to indicate the max possible points)

Description	Value	Max Possible		Team M2	
		Number	Points	Number	Points
Ping Pong Balls					
Gutter	5	**18**	**90**	9	45
End Zone	4	18	72	9	36
Loose	1	18	18	0	0
Toilet Paper Tubes					
Gutter	5	**3**	**15**	0	0
End Zone	4	3	12	2	8
Nests					
Gutter	5	**5**	**25**	0	0
End Zone	4	5	20	1	4
Poof Balls					
Gutter	5	**3**	**15**	0	0
End Zone	4	3	12	0	0
Penalties					
Touching	-1	5	-5	2	-2
Totals					
		Max Total	**145**	Team M2 Total	91

Case Study Summary

It seems reasonable to conclude that Team M2 was an exceptional team, with some previous competition experience among its team members, students who were generally considered smart and good at math, and an experienced mentor. Nevertheless, it also seems clear that a big part of Team M2's success was a direct result of their use of math in their solution strategy, and that their math use gave them real advantages at multiple levels.

Our hypothesis is that a team that uses math effectively to quickly zero in on correct motor rotation values in their program can save valuable time. That time can then be used to make the

rest of the robot more efficient and reliable, or even build a second specialized one to complement the first. In addition, using math as a larger strategy to do more systematic analysis of the points breakdown and the effectiveness of different mission solutions can have a major impact on a team's maximizing its performance at the competition.

Learning and Attitude Benefits of Using Math

Not every team will have the background to apply math as effectively as Team M2. After all, the results reported above show that there were teams who tried to use a math-based strategy but ended up performing poorly (refer back to Figure 2), including the elementary age Team E2. In addition, the results also show that the *View-Mode* strategy, which doesn't include any math, was the most straightforward, reliable, and effective strategy on average (refer back to Figure 2 again). A possible implication from this may be that only teams of students who are older or who have higher levels of prior mathematics achievement should even attempt to use math in their solution strategy. Otherwise, the students may not be capable of applying the math effectively. Although these data support this conclusion in terms of competition success alone, there may be other benefits to a team that uses math despite this.

Returning again to the full set of *Focus Teams*, there was a convenient contrast in that two of the teams used a math-based strategy (Teams E2 & M2) for their first move, and the other two teams (Teams E1 & M1) used a non-math-based strategy. By comparing these sets of teams we can test whether using math is associated not only with competition success, but also with other outcomes.

The Learning Benefits of Using a Math-Based Strategy

Figure 3 shows the results from the *Robot Math Survey* administered to the *Focus Teams*. The middle school age teams (Teams M1 & M2) have higher scores overall than the elementary school age teams (Teams E1 & E2), which is not surprising. The older students have more experience with mathematics in general, and it shows when they solve formal problems that make use of math.

However, a more interesting pattern can be found by looking not just at the scores, but also at the gains. The two teams that used the math-based *Calculate-Test-Adjust* strategy—Team E2 ($t(3) = 3.65$, $p = 0.04$) and Team M2 ($t(8) = 3.05$, $p = 0.02$)—both improved on their survey scores from the beginning of the competition to after, but the teams who used a non-math-based strategy—Teams E1 and M1—did not improve. This overall pattern suggests that regardless of a team's initial level, using math in an explicit way in the competition design solution improves student use of math when solving more general problems relating to robot movements. If increasing students' problem solving abilities using math is a goal of the robot team, then just attempting to use a math-based strategy may have real advantages, regardless of how it impacts the team's overall success in the competition.
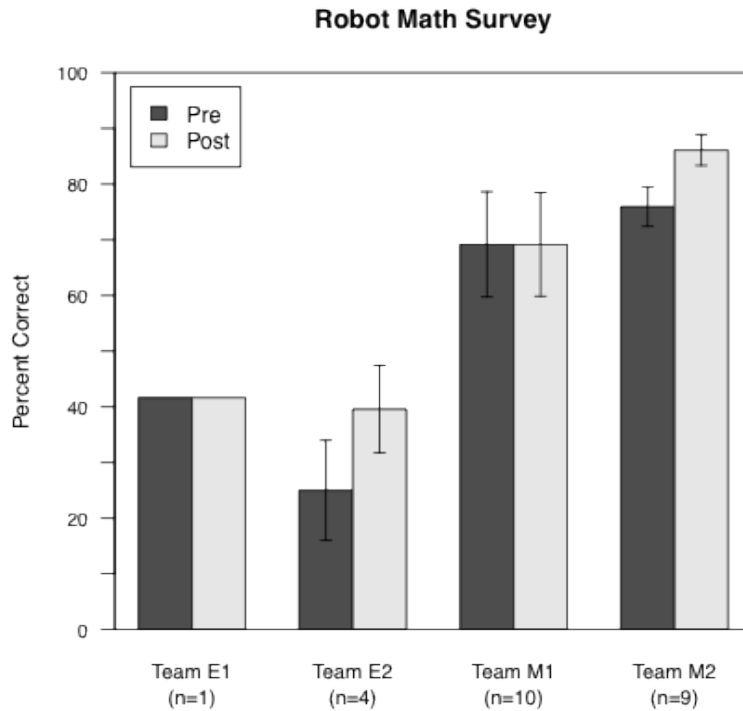
Robot Math Survey

Figure 3: Robot Math Survey Pre-Post Results for the Focus Teams

The Attitude Benefits of Using a Math-Based Strategy

The *Robot Attitudes Survey* measured students' attitudes toward math and robots in general (see Figure 4). Team E2 was the only one of the 4 *Focus Teams* that had overall more positive views as measured in the attitude survey after the competition compared to before (t(3) = 4.75, p = 0.02). Team E2 was the elementary school age team that used the math-based *Calculate-Test-Adjust* strategy in their solution. For this team, the experience preparing and competing in the competition did have a statistically significant positive impact on their interest in mathematics (t(3) = 4.37, p = 0.02), and their were positive trends on their interest in robotics (t(3) = 2.10, p = 0.13) and their views about the value of mathematics for robots (t(3) = 1.84, p = 0.16). Given the low number of students in the paired t-test analyses, the impact seems meaningful despite not reaching statistical significance in two of the subscales.

Remarkably, this positive change in attitudes was attained in spite of the fact that Team E2 did not score highly in the actual competition (ranked #17 out of 22 teams). This result echoes a statement by a number of other coaches who, in the day-of-competition team interviews, stressed that they were participating to provide their students with a positive experience working with robots, not to win the competition. It appears, though, that by using mathematics in the robotics competition, attitudes toward math itself may benefit as well.
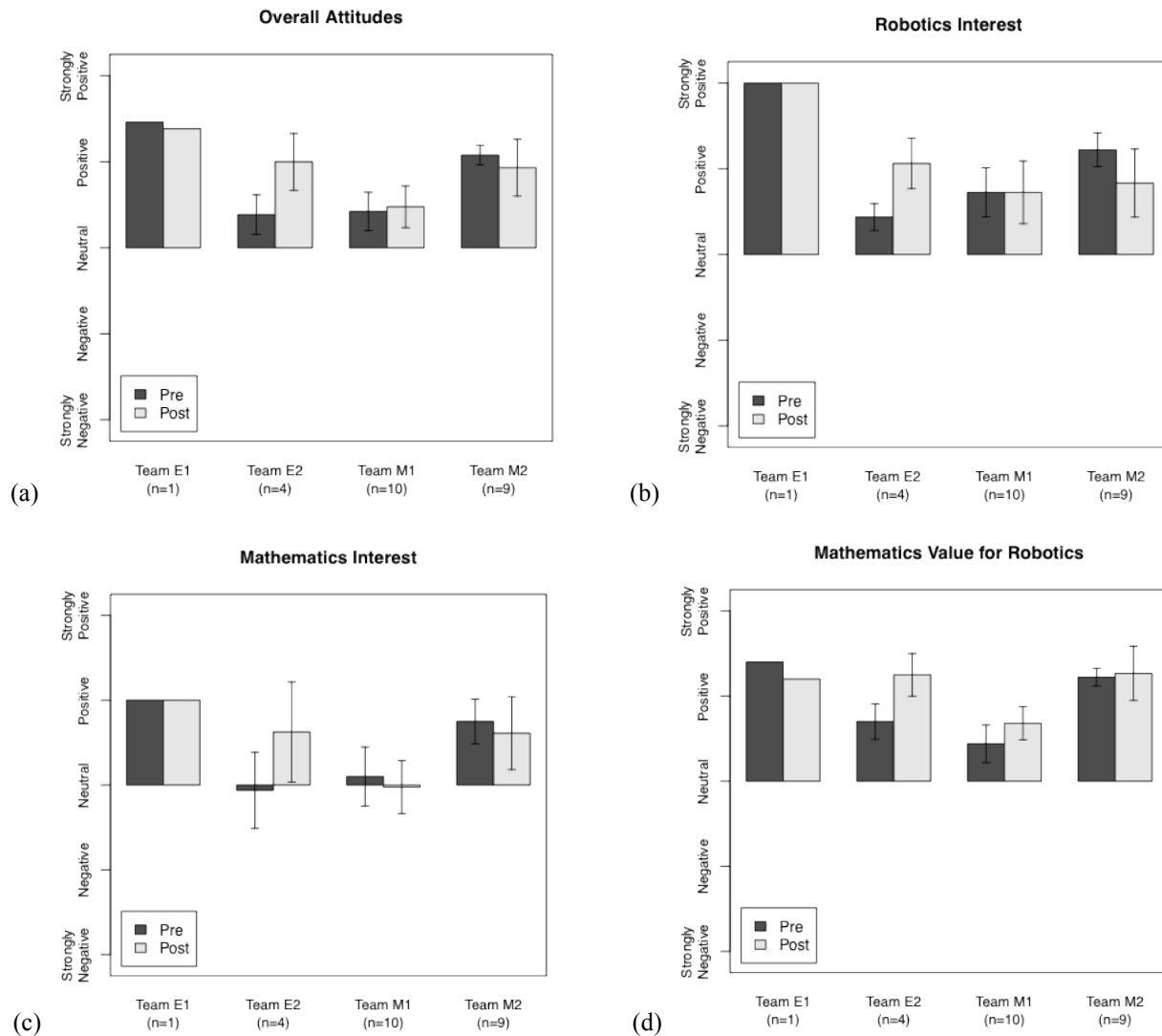
Figure 4: Focus Teams *Survey Results on Students' Change in Attitudes About Robots and Math*

Conclusion

To summarize the results, only a few teams used math explicitly in their design solutions. The use of math was found to have a highly variable relationship with design success, with the highest and very low scoring teams in the competition having used math. When considering other outcomes in the teams followed in more depth, regardless of whether math was used successfully or unsuccessfully in their solution designs, the teams that attempted to use math exhibited improved performance on the transfer test of robot math problem solving whereas the teams that did not attempt to use math did not exhibit gains. Further, even in the case where a team used math in the solution design but did not have success in the competition, the students' interest in math and in robots as well as their views about the value of math for robots was more positive after participating in the experience.

Certainly there are some caveats and limitations to this study. The small number of teams included—and the even smaller number of *Focus Teams*—makes drawing definitive conclusions difficult. One possible concern may be about confounding factors that may be better explanations of success than use of the math-based solution strategy. For example, it is possible that Team M2's success may be more about their general level of ability than their math use specifically. Although we cannot rule out this possibility, it is worth noting that Team M1 is similar to Team M2 in many ways. They are both school-based teams, are middle school age, are from high-achieving suburban districts, and have very experienced coaches. If anything Team M1 has advantages over Team M2 in a number of factors, such as devoting more time to preparing for the competition and a greater number of experienced students on their team. And yet, Team M2 still outperformed Team M1. Again, these are only two cases, but the difference in math use still remains as a plausible explanation for their difference in success. We have conducted some follow-up analyses on these data using multiple regression suggesting that math use is just as predictive for explaining a team's success as many other common factors. That isn't to say math use is the only important factor, but that the evidence is suggestive that it does matter.

Further research in this area would certainly look at a larger number of teams to try to tease apart the level of influence of these different factors. It would also be valuable to test some of our hypotheses about the reasons why math use leads to success (i.e., that applying math-based strategies correctly and efficiently frees up resources that can be devoted to other equally-important aspects of the task) by collecting more data about the processes that team's use when creating their solutions. Do teams that use math spend less time getting their robot movements fine-tuned? Does that lead to spending more time on fine-tuning the physical robot design or their high-level strategy in terms of which missions to pursue in which order? It would also be valuable to collect more in-depth data on teams that are not successful using math for the competition, but still exhibit positive outcomes on other measures.

This study was focused on investigating aspects that may contribute to a team's success in a robot competition. Being older and better at math both seem like advantages for teams in a robot competition. But just attempting to use mathematics in a team's design solution strategies, however, also seems to be important. Every coach has this option, and it appears to be associated with both direct and indirect outcomes. A team with a high degree of fluency in mathematics can apply math in creative ways directly related to programming their robot behaviors and this may lead to better performance in the competition. A team that is less fluent in mathematics but commits to using math anyway sets itself up for a different kind of success – real, measurable gains in student problem-solving capability and attitudes toward robots and math. If, in trying to create more systematic solutions, students' failed attempts actually help them to understand more about the way the robots work, they may be able to apply those improved understandings to future problems. If, in the challenge of attempting to use math, a student comes to understand the role or context of mathematics better, it may make both robots and mathematics more interesting, and may help the student to see math as having real, usable value for robots and in the world more generally.

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Appendix A

Robot Math Survey

To measure students' ability to use math in robot transfer problems, a 12-item paper-and-pencil survey was created. The survey consisted of both multiple-choice and short-answer questions targeting proportional reasoning in the prediction and control of simple robot movements. The items were modified from validated assessments of proportional reasoning[11, 12] to include a robot motion cover story. For each item, students were given a blank line to write their answer and then blank space below that where they were asked to show their work and explain how they found their answer.

1. *How many motor rotations has Alexa's robot done?*

    Alexa downloaded the same program to two identical robots. First, she starts one robot. A few moments later she starts the second robot. By the time the first robot had done 7 motor rotations, the second robot had done 3 motor rotations. How many total motor rotations will the first robot have completed by the time the second robot has completed 12 motor rotations?

2. *If you change the motor rotations, how far forward now?*

    A robot completes a move with 12 motor rotations and moves forward 14 centimeters. You modify the program to be 30 motor rotations. How far will it move forward now?

3. *How many for movement B?*

    Three different movements are programmed into a robot.

    > A: Move 15 *cm* straight forward ⟶
    > B: Move 10 *cm* straight forward ⟶
    > C: Move 5 *cm* straight forward ⟶

    If it takes 2 motor rotations to do movement C, how many motor rotations are needed for movement B?

4. *How many rotations are needed?*

    A robot moved forward 6 centimeters when it was programmed to do 4 motor rotations. The programmer needed to make her robot move forward 24 centimeters. How many motor rotations does she need to enter in her program to do her move correctly?

5. *How tall is Mr. Tall in paper clips?*

    You can see the height of Mr. Short measured with paper clips. Mr. Short has a friend Mr. Tall. When we measure their heights with matchsticks:

    > Mr. Short's height is four matchsticks.
    > Mr. Tall's height is six matchsticks.

    How many paper clips are needed for Mr. Tall's height?

    Mr Short
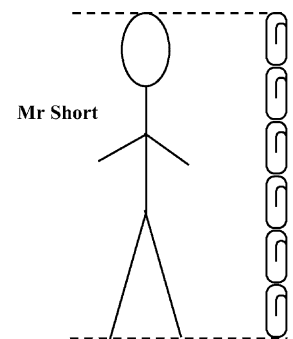
6. *If you change the wheels, how far forward now?*

    A robot has a wheel circumference of 3 centimeters. The programmer successfully gets the robot to move forward 90 centimeters. The programmer then

puts on new wheels with a wheel circumference of 7 centimeters and runs the same program. How far will the robot move forward now?

7. *How many motor rotations when the motor speed is different?*

Alicia has two different robots both with super-fast motors. Alicia gets her programs working so that the robots start and complete a move at the same instant as each other. Her first robot moves at a motor speed of 10 motor rotations per second and completes the move with 50 motor rotations. Her second robot moves at a motor speed of 30 motor rotations per second. How many motor rotations did Alicia's second robot complete for that move?

8. *How many dictionaries can it print?*

A printing press takes exactly 12 min to print 14 dictionaries. How many dictionaries can it print in 30 min?

9. *Which robot moves further?*

Robot A has wheels with a circumference of 3 centimeters and is programmed to do 3 motor rotations. Robot B has wheels with a circumference of 4 centimeters and is programmed to do 2 motor rotations. Which robot moves further?

   a. Robot A moves further.
   b. Robot B moves further.
   c. They move the same distance.

10. *Which robot needs more motor rotations?*

Robot A moves forward 10 centimeters in 4 motor rotations. Robot B moves forward 15 centimeters in 6 motor rotations. Which robot will need more motor rotations to move forward a distance of 40 centimeters?

   a. Robot A will need more motor rotations.
   b. Robot B will need more motor rotations.
   c. They will both need the same number of motor rotations.

11. *Does Ed's rule work?*

Ed got his robot working for one movement through trial-and-error. He got it to move straight forward 4 centimeters by programming it to do 10 motor rotations. Instead of doing trial-and-error again, he wanted to predict how many motor rotations he would need to put in his program to get his robot to go 6 centimeters. He said:

   I know that when I want my robot to go further I need to add more motor rotations. Since 10 motor rotations gets me 4 centimeters, and 6 is two

*more than 4, I need to add two to the motor rotations also. 10 plus 2 is 12.
That is why I think 12 motor rotations will work.*

Do you think Ed's idea works? If you do think his idea works, then explain why it
makes sense. If you don't think his idea works, then explain why not and what he
should do to fix his idea.

   a. Yes, I do think Ed's idea works.
   b. No, I don't think Ed's idea works.

12. *Will one of Michelle's robots ever be twice as far as the other?*

Michelle has two robots that she sets up side-by-side at the start line. She
programmed them to move at the same motor speed straight forward and to keep
moving until she pressed the stop button. One robot has a 3-centimeter wheel
circumference and the other has a 5-centimeter wheel circumference. Will one
robot ever be twice as far as the other robot from the start line? If so, which robot
and when? If not, explain why not?

   a. Yes, one robot will eventually be twice as far as the other robot.
   b. No, one robot will never be twice as far as the other robot.

Appendix B

Robot Attitude Survey

To measure attitudes towards robots and math a 13-item, paper-and-pencil survey was created.
All of the items were 5-point Likert scale items that were modified from a validated inventory of
attitudes towards mathematics (ATMI).[13] All of the items used in the attitude survey are included
in the table below. Each item was presented with the choices: *Strongly Disagree*, *Disagree*,
Neutral, *Agree*, and *Strongly Disagree*.

Item	Text
Robotics Interest	
RI2	I enjoy working on robotics problems
RI2	I would even give up some of my spare time to learn new topics in robotics
RI3	While working on a robotics problem, it sometimes happens that I don't notice time passing
RI4	Robotics is dull and boring *(reverse coded)*

Item	Text
Math Interest	
MI1	I enjoy working on mathematical problems
MI2	I would even give up some of my spare time to learn new topics in mathematics
MI3	While working on a mathematical problem, it sometimes happens that I don't notice time passing
MI4	Mathematics is dull and boring *(reverse coded)*
Math Value for Robotics	
MVR1	I can think of many ways to use math in robotics
MVR2	Mathematics is one of the most important subjects for people to study if they are interested in robotics
MVR3	Mathematics helps teach a person to think about robotics
MVR4	I believe studying math helps me with problem solving in robotics
MVR5	Mathematics is sometimes useful but not that important in robotics *(reverse coded)*

Appendix C

Design Strategy Questionnaire

To obtain descriptive information on each team at the competition a researcher-administered interview questionnaire was created. The goal of the survey was to obtain information about number and experience levels of students and mentors in addition to their solution strategy.

1. *Number of Students (put a count next to each one)*

    a. # of 8th graders?
    b. # of 7th graders?
    c. # of 6th graders?
    d. # of 5th graders?
    e. # of 4th graders?
    f. # of 3rd graders?
    g. # of 2nd graders?
    h. Other? (describe)

2. *Competition Experience of Students (put a count next to each one)*

   a. # of Rookies?
   b. # w/ 1 Prior Competition?
   c. # w/ 2+ Prior Competitions?

3. *Number of Mentors/Coaches (put a count next to each one)*

   a. # of Professionals w/ robotics-related background?
   b. # of Teachers w/ robotics-related background?
   c. # of Professionals w/o robotics-related background?
   d. # of Teachers w/o robotics-related background?
   e. Other? (describe)

4. *Competition Experience of Mentors/Coaches (put a count next to each one)*

   a. # of Rookies?
   b. # w/ 1 Prior Competition?
   c. # w/ 2+ Prior Competitions?

5. *Hours Team has Met in Preparation (put a count next to each one)*

   a. # Prior to Last 2 Weeks?
   b. # in Last 2 Weeks?
   c. # in Total?

6. *Programming Platform (choose all that apply)*

   a. NXT-G?
   b. ROBOTC?
   c. LabVIEW?
   d. easyC?

7. *Robot Platform (choose all that apply)*

   a. LEGO RCX?
   b. LEGO NXT?

8. *Robot Base Design (choose one)*

   a. Tankbot (RCX)?
   b. Robotics Educator (NXT)?
   c. Taskbot (NXT)?
   d. Domabot (NXT)?
   e. Completely original design?
   f. Other? (describe)
   g. Did you adapt it? (yes or no)
   h. If you did adapt it, how? (describe)

9. *Solution Strategy Straight – At any point in your solution, does your robot have to straight a specific distance? (yes or no)*

    a. What is the game context? (describe)
    b. Did you measure how far it has to go? (yes or no)
        i. If you did measure it, how far?
    c. What sensor did you use for that movement? (choose one)
        i. Touch?
        ii. Rotation?
        iii. Timer?
        iv. Sound?
        v. Light?
        vi. Ultrasonic?
    d. How did you determine the value for the sensor?
        i. N/A?
        ii. Unsystematic guess & test?
        iii. Systematic guess & test?
        iv. Proportion calculation?
        v. Overshoot?
        vi. Other? (describe)

10. *Solution Strategy Turns – At any point in your solution, does your robot have to turn a specific amount? (yes or no)*

    a. What is the game context? (describe)
    b. Did you measure how much it has to turn? (yes or no)
        i. If you did measure it, how much?
    c. What sensor did you use for that movement? (choose one)
        i. Touch?
        ii. Rotation?
        iii. Timer?
        iv. Sound?
        v. Light?
        vi. Ultrasonic?
    d. How did you determine the value for the sensor?
        i. N/A?
        ii. Unsystematic guess & test?
        iii. Systematic guess & test?
        iv. Proportion calculation?
        v. Overshoot?
        vi. Other? (describe)

11. *Solution Strategy Manipulators – At any point in your solution, do the manipulators on your robot have to move a specific amount? (yes or no)*

    a. What is the game context? (describe)
    b. Did you measure how much it they have to move? (yes or no)

       i. If you did measure it, how much?
- c. What sensor did you use for that movement? (choose one)
  - i. Touch?
  - ii. Rotation?
  - iii. Timer?
  - iv. Sound?
  - v. Light?
  - vi. Ultrasonic?
- d. How did you determine the value for the sensor?
  - i. N/A?
  - ii. Unsystematic guess & test?
  - iii. Systematic guess & test?
  - iv. Proportion calculation?
  - v. Overshoot?
  - vi. Other? (describe)

12. Other Strategies

- a. Thinking of the behaviors above, did you try a different way to determine the value for the sensor that didn't work? (yes or no)
  - i. Yes? (describe)
- b. Did you ever try to use math for determining the value for the sensor? (yes or no)
  - i. Yes? (describe)
- c. Did you ever use math in any other aspect of your work preparing for the competition? (yes or no)
  - i. Yes? (describe)