International Journal of Social Robotics

Between the Social and the Technical: Negotiation of Human-Centered Robotics Design in a Middle School Classroom

--Manuscript Draft--

Manuscript Number:	
Full Title:	Between the Social and the Technical: Negotiation of Human-Centered Robotics Design in a Middle School Classroom
Article Type:	S.I. : Special issue on robots for Learning
Keywords:	human-centered robotics; STEM education; problem-based learning; sociotechnical systems; engineering design cycle; qualitative case study
Corresponding Author:	Andrea Gomoll Indiana University UNITED STATES
Corresponding Author Secondary Information:	
Corresponding Author's Institution:	Indiana University
Corresponding Author's Secondary Institution:	
First Author:	Andrea Gomoll
First Author Secondary Information:	
Order of Authors:	Andrea Gomoll
	Selma Šabanović
	Erin Tolar
	Cindy Hmelo-Silver
	Matthew Francisco
	Orion Lawlor
Order of Authors Secondary Information:	
Funding Information:	National Science Foundation (DRL-1433414) — Dr. Selma Šabanović
	National Science Foundation (DRL-1433841) — Dr. Selma Šabanović

Between the Social and the Technical: Negotiation of Human-Centered Robotics Design in a Middle School Classroom

Andrea Gomoll[2], Selma Šabanović[1], Erin Tolar[2], Cindy Hmelo-Silver[2], Matthew R. Francisco [1], Orion Lawlor[3]

[1]*School of Informatics and Computing*
Indiana University
901 E. 10th. St.
Bloomington, IN, USA 47408

[2] *School of Education*
Indiana University
201 E. Rose Ave.
Bloomington, IN, USA 47405

[3]*College of Engineering & Mines*
University of Alaska Fairbanks
PO Box 756660
Fairbanks, AK 99775

Corresponding Author
Andrea Gomoll
1900 E. 10th St., Office 536
Bloomington, IN, 47405

agomoll@indiana.edu
(414) 531-4901
ORCID: 0000-0002-6360-6742

Acknowledgement: This research was funded by National Science Foundation awards DRL-1433414 and DRL-1433841. We acknowledge the contributions of Haley Molchan, Stella Huang, Charlie Mahoney, AnnaRose Girvin, Miranda Meade, and Ben Oistad who played a key role in the implementation of our curriculum.

Abstract

This paper presents a secondary school human-centered robotics (HCR) learning experience and the ways in which it supported students' orientation to technical and social aspects of Science, Technology, Engineering, and Mathematics (STEM). The interdisciplinary project associated with this analysis aims to engage students in authentic STEM practices by creating robotic technologies that can assist people in their school, as well as connect with remote peers. The goal of this project is to increase student interest in and knowledge of STEM topics, and to help students recognize STEM as relevant to their daily lives and broader societal issues. The human-centered focus of the curriculum encouraged thinking from multiple perspectives (e.g. design, social science, programming) and allowed for diverse STEM exploration. We present samples from student work and interaction to show challenges and successes in engaging students with STEM as a combination of social and technical questions and skills. We trace the trajectory of one group's work to highlight moments in which students navigated an engineering design cycle, analyzed and designed social environments, and crossed disciplinary domains through HCR design—using a component, mechanism, phenomena framework (CMP) to explore systems thinking. *Components* included a focus on single parts of the robot, *mechanism* addressed how parts of the robot worked together, while *phenomena* included attention to the function of the robotic technology in the classroom environment. This qualitative case study demonstrates the capacity social robotics and inquiry-based learning experiences hold for broadening notions of STEM as a social and multidisciplinary learning domain.

Keywords: human-centered robotics; STEM education; problem-based learning; sociotechnical systems; engineering design cycle; qualitative case study

Introduction

Robotics has become an increasingly popular topic for introducing children of all ages to a variety of disciplinary principles—from STEM to social skills [1-6]. Providing students with opportunities to learn through hands-on robotic applications has been effective in engaging diverse groups of students with technology, including female [7] and minority populations [8]. Although robotics is expected to have broad societal application in the future, K-12 robotics curricula still regularly focus largely on the development of technical skills and knowledge without much reference to the social and cultural contexts in which people practice and experience them [7]. This technology-only focus limits the opportunity for using robotics to engage a wide and diverse audience in STEM and impedes the development of STEM disciplines themselves.

In this paper, we present a human-centered robotics curriculum designed around the identification of an authentic social problem in students' everyday school environment that robotics can help them understand and address through telepresent interaction. Human-centered robotics (HCR)—the development of robots that provide services and assistance to people in their daily lives [9]—provides us with an application context that combines the need to understand technical aspects of robots with the desire to address social needs and concerns. This approach is motivated by the recognition that, to broaden participation and interest in STEM, we need to go beyond the focus on technical achievements. "Human-centered" applications in particular should motivate and enable diverse groups of students to explore the intricacies of scientific principles and technology design as they consider how these principles can be used to improve their social worlds [10]. For example, researchers found that novice users designing their own robotic technologies within sociotechnical systems were able to question their own assumptions about the social and physical world [11]. In another example, Hamner et al. [7] found that robots students can use interactively to express themselves and communicate with others are motivational for female students. This suggests that socially relevant uses for robots can be particularly successful in motivating participation in STEM among a broader set of learners, including those who have not previously expressed an interest in technology and those currently underrepresented in STEM fields (e.g. women and ethnic minorities).

Building on prior educational successes with robotics, and the promise of human-centered robotics in particular, our HCR curriculum creates a robotics experience to help learners develop technical skills along with an understanding of the relationship between technology, nature, and society. We designed this unit to support students as they considered both social and technical aspects of STEM. As students engaged in the design of human-centered robots, they situated robots meaningfully in social spaces. As they worked together to solve a problem, we conjectured that students would be motivated by the opportunity to serve a need in their local environment and by the possibility of personalized technology design. Early iterations of our curriculum showed opportunities to personalize during robot design promoted engagement with STEM principles and practices [12]. This motivation stands in contrast to the common practice of using robotics *competitions* to motivate K-12 students' involvement in STEM [7].

In much robotics work, technical issues provide an abundance of structured problems that often result in research and development that focuses on technical concerns. This focus is often paired with the expectation that social benefits will occur as a result of technical improvement [13]. In K-12 learning environments, the immediacy of technical challenges can overshadow the exploration of nuanced social considerations, as students do not take time to consider the larger functions technical components might have in the operational context that surrounds them. Our work aims to replace this technocentric trend with a sociotechnical perspective. To do this we used a problem-centered approach aimed at supporting the variety of ways that humans can build robots and create robotics knowledge. We argue that this approach can prepare students to do work in STEM fields, and to contribute to the development of socially responsible and robust robotics technologies. This "epistemological pluralism" acknowledges that seemingly rote and technical practices (e.g. computing) are embedded within social systems that include diverse knowledge practices and values [14]. Orienting students to these systems in a flexible, problem-centered way can bring a more diverse population of students into the discussion and development of robot designs for society.

This paper seeks to present tangible examples of the ways our human-centered robotics curriculum has supported students' exploration of social *and* technical aspects of robotics design and development, as well as where improvements can be made in this HCR curriculum and beyond. In particular, we ask:

1) In what ways does a problem-based and human-centered robotics experience engage secondary school students in the social aspects of STEM?

2) How does our implementation of an HCR curriculum inform broadening notions of what STEM learning can and should look like?

In the qualitative case study that follows, we trace the trajectory of one group's work throughout the HCR unit to highlight moments in which students navigated an engineering design cycle, analyzed and designed for the social environments around them, and crossed disciplinary domains through human-centered robot design. We first provide background and details about our curriculum, and then present our analysis of students' engagement with the social and technical aspects of robotics as they worked with our materials.

A Problem-Based HCR Curriculum

Building on the capacity of HCR to motivate engagement and interest in STEM in epistemologically pluralist ways, our research team developed a curriculum of robotics experiences that stems from a human-centered problem posed as a design challenge ("How can we create a robot that serves a need in our local context and can be used to connect with remote peers?").

Problem-based learning (PBL) is the inquiry-based pedagogical strategy that framed our curricular design. PBL situates learning in collaborative groups faced with ill-structured problems, and it features a facilitator who guides the learning process [15]. PBL has been used effectively to address design problems [16-17]. The problems posed by HCR are an excellent fit for PBL, as they are "wicked" problems that are complex, multi-faceted, indeterminate, and occur in open systems [18]. In our curriculum, students design robotic systems to fit into real contexts of use, which they study as they develop and evaluate their telepresence robot designs. As they attempt to understand and define a design problem, students learn to negotiate the complexity of sociotechnical issues and decide among competing possibilities. Students articulate their choices using scientific reasoning and critical thinking strategies as they assume responsibility for the technical *and* social consequences of their designs. Throughout this unit, inquiry-based pedagogical strategies guided student thinking and interactions [19, 15]. These strategies ask students to grapple with their design, collect data, create artifacts, and communicate developing ideas, helping them to build knowledge about what it means to collaborate and solve complex problems.

The design and structure of our unit is informed by several engineering and crosscutting aspects of the Next Generation Science Standards (NGSS), a set of increasingly implemented educational science standards in the US [20]. NGSS recognizes that students must grapple with system components as interdependent. In addition, NGSS includes a focus on engineering design as a practice. Throughout our HCR unit, students consider the connection of robotic components to their function in the physical system of the robot a*nd* the social system of the human environment as they engage in design. As students troubleshoot, they must consider human expectations and habits in addition to trial and error technical testing. As they move through an engineering design cycle [21], they define and delimit an engineering problem, develop possible solutions, and optimize designed solutions. As part of this approach, students are expected to consider these elements as they construct an explanation of why their design works for other people.

HCR Unit Trajectory

Our HCR curriculum has been implemented in Indiana and Alaska, in both formal (five middle and high school classrooms) and informal (one after school club) contexts, starting in spring 2015. Initial analyses of the implementation of an early version of our curriculum in the informal context of an after school club provided evidence that the model shows promise for engaging female students in robotic design [12]. Our HCR unit includes five major components: brainstorming and exploring, mapping, embodied programming, designing, and building. These components of the curriculum are taken up differently by each instructor—adjusted to fit prioritized educational standards, timeline, and classroom culture. All implementations make use of the iRobot Create 2 platform and a robotics stack called "Robotmoose."[1] This paper focuses on the specific version of our curriculum that was carried out in an Indiana middle school Applied Science classroom in the fall of 2016. In Table 1, we briefly describe each of the five sections of our curriculum as they were performed in this particular classroom.

[**Table 1** HCR Curriculum Trajectory. See end of document for Table 1 contents]

[1] The iRobot Create 2 platform (nicknamed KT in classroom contexts) serves as the base for each group's design. Each standard KT is made up of an iRobot Create 2, an Arduino Mega, a Chromebook, and a mounting bracket for these parts. Students use a web interface to establish a video call with the robot from another computer, drive the KT using keyboard controls, and create programs to script behaviors. The system makes it possible for students and teachers to create personalized and functional mobile telepresence robots. KT is controlled using the RobotMoose web robotics stack. This architecture includes a front end web interface called RobotMoose or Frontend, a web database server called Superstar, a Chrome app called Backend onboard the robot, and a configurable microcontroller firmware called TabulaRasa (Francisco et al., in progress).

Methods of Data Collection and Analysis

Participants & Data Sources

Participants included 16 students in a five-week HCR unit in a 7th and 8th grade Applied Science class held in fall 2016 in a rural U.S. public school. Each class session was approximately 50 minutes long, and the class was divided into four small groups for the duration of the unit. Five students identified as female, and 11 as male. All student artifacts were collected throughout the unit (e.g. design drawings, daily reflective responses). Many of these artifacts were stored in the learning management system Canvas. Video that captured the whole class was recorded for each class session; video footage was also collected for two focus groups during each class period. The instructor selected these focus groups—prioritizing groups that were comfortable speaking in the presence of a camera. All student groups were audio recorded during each session.

Data Analysis

We investigated our research question through mixed qualitative methods. We drew upon tenets of interactional ethnography, video analysis, and interaction analysis. Our research team first worked to explore where students *ended up* in the unit based on their final products in order to inform tracing back how they got there. This approach was inspired by work in interactional ethnography—a qualitative methodology in which a moment or representation is triangulated with pieces of rich data that came before it in order to tell a story about learning [22]. Following the video and interaction analysis recommendations of Powell, Francisco, and Maher [23] and Jordan and Henderson [24], we identified critical events related to the negotiation of social and technical aspects of the curriculum and how they connected to students' end products and presentations.

In the first stage of our analysis, we held two interaction analysis sessions in which all four student groups' final design drawings and presentations of their robots were analyzed by the research team. Presentation clips were transcribed and analyzed following Jordan and Henderson's process [24]. Participants in the data sessions noted interesting features of each interaction and highlighted students' attention to human-centered and social aspects of the design, success and frustration with technical difficulties, and negotiation of teamwork. In these sessions, we identified one student group's transition from an abstract and technically focused robot design drawing to the articulation of connections between social and technical aspects of their robot in the final design presentation. We wondered: What sparked this group's shift? What supported their negotiation of technical and social aspects of this experience? We opted to zoom in on this group's activity for the analysis presented here by first compiling all drawn artifacts created by the group. These artifacts, completed throughout the unit, were used as a series of checkpoints. We held a group data analysis session to examine these artifacts. The research team, which included several undergraduate and graduate students who observed and facilitated in the classroom environment, referenced relevant memos that surrounded these artifacts and recalled interactional details that helped to interpret their content. We then explored the annotated overview of each class period and video data surrounding these artifacts in order to triangulate our recalled interpretations about the ways in which the in-class interaction and PBL class structure informed the students' final designs.

In this emergent data exploration, we developed common language for identifying how students were grappling with technical and social aspects of robot design. This language was informed by the conceptualization of components-mechanism-phenomena (CMP) by Sinha, Rogat, Adams-Wiggins, and Hmelo-Silver [25]. CMP considers components as individual pieces of a system, phenomena as overarching patterns, and mechanisms as the link between components and phenomena (i.e. *why* and *how* the phenomena occur). We adapted CMP to fit our designed HCR context—using it to get a sense of how students were moving towards systems thinking as they connected social and technical aspects of the problem at hand. CMP provided a framework for seeing shifts in students' reasoning. We used "components," "mechanism," and "phenomena" to label what we saw within student artifacts, actions, and utterances throughout the data set. Attention to *components* included a focus on single parts of the robot, *mechanism* was flagged as a consideration of how two or more parts of the robot worked together, while a focus on *phenomena* included attention to the function of the robotic technology and the way it would serve a purpose and interact in the classroom environment. Phenomena was used in Sinha et al.'s work describing natural systems [25], and we adapted this term to reference function in the human environment for our current research. In our human-centered robotics unit, we hoped to see evidence of all CMP levels, but we designed the activities and scaffolds to support frequent connection to *phenomena.*

Findings

In the sections that follow, we present key extracts from each of the four groups' final presentations and design drawings to highlight where they ended up. Though all groups achieved a human-centered connection at the phenomena level, the presentations varied in their explanation of components and mechanisms. We provide a description of each group's final presentation and then trace the trajectory of one group's work at several time points throughout the HCR unit to highlight moments in which students navigated the engineering design cycle, analyzed and designed for the social environments around them, and crossed disciplinary domains through HCR design. We address group design drawings as an additional data point. Prior to students' building process, they were asked to individually brainstorm robot designs and come to a group consensus about which design they would ultimately create. These group designs could combine elements of several individual student designs. When consensus was achieved, each group created an orthographic design drawing (top, front, and side views) to represent their imagined human-centered robot. We turned to these final drawings as evidence of the 4 groups' attention to social and technical aspects of robotics. In tracing back to this group artifact, completed 7 days before the final presentation, we gained a sense of the group's initial shared orientation to the technical and social that may or may not have come through in their final presentations and products. This informed our decision to focus on one group in particular (Group 3) that had a disconnect between their design drawing and what they ultimately built. These data points are presented as moments in which students moved between the technical and the social to uncover the complexity of the design problem. This qualitative case study demonstrates the capacity social robotics and inquiry-based learning experiences hold for broadening notions of STEM as social and multidisciplinary.

In this paper, we highlight extracts of final presentations from Groups 1, 2, and 4, and then present Group 3's presentation and design drawing in order to support our decision to focus on this group.

Recycling, Nurses, Papers, and Books: Four Groups' Final Presentations

On the final day of the 5-week HCR unit, students were challenged to present and demonstrate their robot designs. Students prepared to speak about their robot's purpose, the inspiration behind their designs, their target robot user, and their design process. In

Figure 1, we see the finished HCR robots lined up proudly across gray tiles at the front of the classroom during this culminating class period.

[**Fig. 1** Final robot presentations]

In the following extracts from each presentation, we hear the students speak about their social and technical considerations and how these considerations were embodied in the physical robot prototypes shown in Figure 1.

Group 1: Trash Recycling robot

Group 1's robot stands approximately three feet tall and features large block letters that spell "Trash" and "Recycling" across the robot's cardboard body. The four students in this group designed their robot to collect trash and recycling from student groups throughout a class period. This design was selected when the group recognized a need to keep their classroom clean, which would benefit the environment at large. About two minutes into their presentation, students Martha, Annie, and Odin[2] discussed their design process—honing in on the importance of troubleshooting. In this short interaction, we see how these students focused on components and mechanisms—attending to their robot's balance, stability, and the specific parts that made this possible. As the students reflected, they used a picture of the engineering design process to structure their response. This image featured the following categories: Imagining, asking questions, collecting information, developing and testing solutions, and improving [21].

Martha: ...Um, how did you overcome these challenges? We tried a lot of different ways. For the stableness, we had to add the four support bars, which are these *(points to wooden dowel rods on the robot body)*. For making sure it would stay up…we had to make sure everything was even and equal…And for making sure it would get around the tables and everything…we had Annie start calculating the steps.
Odin: …When we asked a question, we asked like how could we get it to stay up, and so when it like jerks backwards, how, how would it not fall…For imagine, we kinda thought up our ideas, kinda drew it out a little bit, see if it would work. To collect information, we… saw what was weak or wasn't as sturdy, and so we added to it. And then, develop and test solutions, after we saw what was weak, we added to it, and if it still didn't work, we added more.

Though group 1's design was based in a human need (disposing of garbage and an environmental commitment to recycling), their articulation of the design process focused on physical components and the work the group did to help them operate together

---

[2] All students have been given pseudonyms.

(mechanism). Here, the technical work of assuring robot stability appeared to overshadow the more human-centered aspects of the unit's final product. For example, Odin mapped *all* pieces of the design cycle to the single issue of stability. Though it is notable that the students were able to identify a learning issue and how they overcame it (an important piece of PBL), the group did not connect the need for stability to the function of their design (phenomena).

Group 2: Nurse assistant robot

Group 2's robot features a protective ring of PVC pipe and a white Styrofoam cooler pulled by three strands of braided yarn. It includes cardboard shelves lined with red felt. Like Group 1, Group 2 focused on technical challenges and solutions in their design cycle reflection. This group created a robot used by the school nurse to transport medication and snacks to classrooms. George, one of two male students in this group, summed up a component-level challenge and how it was addressed through testing:

George: Test solutions. One thing we did was we made a shelf, and we tested it by putting weight on it. When we first made a shelf, we glued it down and it wasn't as sturdy as we needed it to be. So we, by putting poles under the shelf to help support it better, we asked things like, is there any other way to help support the robot, and also…do we…need anything else to make the…robot a success?

In this response, there is orientation to an individual component of the robot—the shelf. This shelf was originally designed to hold medication. The students interpreted "testing" in their presentation in terms of technical trial and error (rather than as a more social user testing experience). Orientation to the social function occurred later in the presentation, but was heavily guided by the instructor. Near the end of the presentation, the instructor provided an anecdote about how this robot could have helped a sick student earlier in the day. This interaction demonstrated the perceived value of the robot design from an authentic user perspective. The students did not build on this connection, but it showed promise for the development of future scaffolds that might support connections like these earlier in the design process.

Group 4: Book robot

Group 4, like groups 1 and 2, focused their final presentation on explaining the technical challenges they faced as they worked to stabilize their robot. Group 4's human-centered purpose was not specific. The students identified a need to hold books in the library, but the group did not provide reasoning for why a human-centered robot would work well for this task. In the interaction below, we hear the group speak to their robot's purpose and abstractly explain their design process:

Matt: The need our robot fills is carrying library books for the librarian in the library
Mark: Ms. [Librarian] needed help in the library, carrying books.
Eli: It's used for students…library users and the librarian.
Matt: People can place books in the library in the top bin.
Mark: …We started with the base of the robot and worked our way up.
Eli: The challenge was balancing the robot…

Here, students attended to both social needs (help carrying books) and technical aspects (balancing components). However, the connection between technical and social was not yet clear.

Group 3: Teacher assistant robot

Group 3's robot towers at the height of classroom tables—topped with a cardboard box emblazoned on one side with red and white pompoms in the shape of the local university logo. In this group's presentation, the connection between CMP was fleshed out further. Group 3 was the only group to code and demonstrate a functioning prototype. They articulated their robot design as a helper for the multitasking teacher. Recognizing that their own instructor often lost valuable class time while collecting student papers, the students imagined a robot that would stop at each table to collect papers from students. This same robot could be used to allow remote visitors to explore the classroom environment via telepresence. The group described the purpose of their robot with a clear social orientation:

Jack: I just felt the need that like sometimes teachers are grading papers and stuff and they don't want to get up to collect everybody else's papers, 'cause they're doing other stuff, so you can reprogram the robot to go to people's desks and pick up their papers and bring them back.
Graham: …Our robot goes to each table and gets… the papers and will take it back to the starting point.
(*The instructor asks who uses the robot. When the group responds that the user is only teachers, the instructor responds)*
Instructor: Students do though, 'cause students don't have to get up and give me their papers anymore.
Jess: All you have to do is press a button that is already coded to the table, and it'll run back for you too.

In this impromptu interaction with the instructor, social and technical aspects of the design were addressed as students touched on both technical coding and social function while considering user workflow. Jess led this consideration as she outlined the simple process their instructor would go through to meet a need in the local environment. This exchange mirrored a first phase of user testing—assessing the user's initial impressions and communicating what the piece of technology could do for them in their everyday lives. The exchange also demonstrated understanding of the connection between the phenomena (the actions of the robot in the space as a teacher aid) and mechanism (programmed buttons as a means of controlling the robot to perform a human-centered task).

Group 3 went on to perform a live demonstration of their robot. This group was able to assemble the physical parts of their robot and to develop programmed buttons for pre-determined sequences of movement (e.g. collect papers from table 1). As the group demonstrated their robot's movement within the class presentation, they ran into a challenge. The robot stopped without turning to face the table and collect papers as intended. Jack directed Graham to "re-run that code." Graham took this direction, and the group members all smiled as their robot returned to its designated starting point and classmates clapped. In this moment, we see evidence of students' internalization and application of the *developing and testing solutions* portion of the engineering design cycle. Rather than asking for help from an authority figure (e.g. instructor or tech facilitator), the students immediately began troubleshooting. Their excitement and success was palpable. Though this group struggled early in the unit to move forward from technical challenges like these, it was clear in this final demonstration that they were comfortable with the iterative process of testing. No longer was this perceived as a failure. The students' experience here with iterative testing is one example of a group's success merging social and technical considerations.

[**Fig. 2** Group 3's robot design drawing]

In our analysis of Group 3's design drawing (Figure 2), we found that it did not reflect what they actually built. Their robot design sketch included a description that highlighted books rather than papers, and it had a laptop positioned at the back bottom section of the robot. There was a considerable transformation from this phase of the group's work to the final presentation of their human-centered robot. It was this transformation, and the group's success connecting technical and social aspects in their final presentation, that spurred our decision to trace this particular group backward, via their artifacts and interactional data.

Zooming in on Group 3

Despite variation in the social and technical emphases that came through in each of these four presentations, each group's design was clearly inspired by the environment that surrounded these students and the social fabric of their everyday lives. One of the central aims of this paper is to give a sense of what our HCR unit looked like through the experiences of one group, particularly how they worked through the social and technical aspects of robot design. In narrowing our focus to one group of 4 students, we are able to tell a rich story about their trajectory and what made their final presentation possible. Building on our data sessions exploring students' final presentations and group robot designs, we selected the group (Group 3) that was able to take their design furthest in the limited time span and that had an interesting transformation between their design drawing and final presentation. This group was also noted in facilitator memos for ownership of their design—working collaboratively to assure that their robot was built and programmed for the final showcase. Finally, Group 3 engaged in preliminary user testing, which provided an especially fruitful opportunity for bridging the social and technical. In the artifact and interaction examples that follow, we highlight Group 3's navigation of the technical and social aspects of robotics design during our human-centered robotics curriculum.

Early robot design drawings

Following the unit's introductory activities and opportunities to brainstorm, students created their individual human-centered robot designs with the understanding that they would be sharing them with their group members and working to convince others that their design should be taken up. In these initial design drawings, we see how students individually attended to aspects of technical and social. Evidence of attention to components, mechanisms, and phenomena in these artifacts speaks to shifts that occurred prior to the final presentation. In Figure 3, we see Jack, Jerry, and Graham's designs. Jess was absent the day that these drawings were created.

[**Fig. 3** Group 3 early design drawings]

Jack's diagram included many labeled parts—attending in detail to the technical components of the imagined robot. This artifact had a "programmable system," a “screen,” “lights,” “body.” It is labeled as “collabsible” (sic). In Jack’s attention to a programmable system, we see depiction of a mechanism—how all of the parts will work together. The noted collapsibility suggests human-centeredness, as do the lights appearing at the base of the drawn robot. Jerry’s design is abstract—focused on a more human-centered function. We see a dishwasher labeled in the center of the robot body. From this, we glean an overarching function for the robot, but we do not yet have a sense of how this function is achieved. This drawing can thus be understood at the phenomena level. Finally, Graham’s drawing appears grounded in social aspects and ecosystems. Multiple human needs have been identified—humans with disabilities who need to carry books, people who have memory loss that could be helped with technology. These details demonstrate a focus on phenomena. It is also notable that Graham included drawn aspects of the environment that surround humans (e.g. shelves with items on them).

At this point in the unit, the students of group 3 had divergent ideas about what would make a functional and useful human-centered robot for their local environment. We turn to written descriptions of these brainstormed ideas to gain a greater sense of how they negotiated their group design and made their way towards the final showcase.

Imagining a robot design: What I know, ideas, what I need to know, and action steps

Following their individual sketches of human-centered robot designs, students were asked to complete a graphic organizer designed to mirror the problem-based learning cycle [15]. Students completed a worksheet which asked them to list the local need that their robot would fulfill, what they know about this need, ideas for the robot design (parts, features), what they needed to know in order to design and build the robot, and next steps for making their ideas into a reality. Students also completed orthographic drawings of their designs at this stage. These two artifacts would be used to help individual students advocate for their design ideas at the group level—working towards consensus for the single robot that each group would ultimately build. Here, we explore these artifacts for evidence of social and technical connections made at the individual level that may have informed the groups’ final robot design and construction.

In his graphic organizer, Jack identified his robot as a robot for giving and receiving books, writing “I know that teachers don’t like handing out 35 books and haveing (sic) them get in the way... So I want it to collect books and give them out.” Jack noticed his teachers’ frustration and imagined a way to alleviate it using technology. In his ideas column, Jack wrote about a big box or crate with "metal rods" that could be used to lift the books up and down. This description attended to the mechanisms of the proposed robot design—considering how the parts would work together to perform a function in the surrounding environment. Jack noted that he needed to know "how to work the rods to lift the books up and down and connect them to the robot." Jack did not identify programming as a means of operating the metal rods, but the process is implicit in his work. In the last column, Jack highlighted planning with his group mates and drawing a model as next steps.

[**Fig. 4** Jack's orthographic drawing]

Jack's orthographic design drawing (Figure 4) featured labeled "extending rods," "book holder/box" and "bars." The drawn design included a laptop placed at the base of the robot body. This drawing closely mirrors the design drawing submitted by the whole team, though it differs from the design that the group ultimately built. In Jack's labeled design features, we see a connection between components and phenomena. Jack noted that the physical component of the box would be used to hold books (the overarching function), and we know from his organizational chart description that the rods in this drawing represent a system for collecting and organizing books from each classroom table.

In her graphic organizer, Jess described her imagined robot as a "robot to be able to take phone calls in the office for when parents call to tell the school kids won't be here today. It could save the office ladies time. It could also write it in Harmony for the absence report." Here, Jess identified a need to streamline school office responsibilities that could be fulfilled by automated technology. She referenced the school's notification management system, Harmony, as a digital tool that her human-centered robot could interface with. This first column considered phenomena and began to address mechanism—*how* the robot would keep track of the calls it took. Jess listed "a forwarder machine, a red light in case someone needs to pick up the phone, a ringtone, and a caller ID screen" as ideas for robot parts and features. These features were likely present in Jess's everyday life—a representation of expectations for the action of "answering a phone," and "leaving a message." Jess attended to the need for environmental cues (red light, ringtone, caller ID screen), and the issue of storage for calls when a human is away from the desk. Each of these considerations takes into account the social human environment and its norms, and maps these norms to technical components. Jess then identified additional information she needed to know—including how many robots would be needed and how often the phone rings.

[**Fig. 5** Jess' orthographic drawing]

Jess' orthographic drawing (Figure 5) labeled a "cable connection," "land line phone," "KT," and "laptop." Each of these labeled components fit into the system that Jess imagined for her human-centered robot. In her short responses and design drawing, Jess attended to human needs, components, phenomena, and usability.

In Jerry's graphic organizer, a human need was identified and an abstract action plan was devised. Jerry titled his robot a book organizer and noted; "The problem is that my robot could help make a better selection of books for us because so many aren't on the shelf." Jerry listed a hand "that can organize," "a spot to pick up books when they might fall," and "speed" as necessary features of his robot. These features are abstract, and Jerry appears to have considered his robot at component (hand) and phenomena (organizing books) levels. He has not yet made a connection between them. He lists knowledge about building a robot as what he needs to know, and "plan and take action" as his action plan.

[**Fig. 6** Jerry's orthographic drawing]

In his orthographic drawing (Figure 6), Jerry labeled a "laptop," "Quizbot parts," the KT robot, and a "hand." It appears that Jerry intended to use parts from an introductory robotics station that occurred early in the unit (Quizbot) to construct the hand he imagined At this stage, Jerry did not demonstrate *how* this would work, but there is evidence that he was beginning to consider mechanisms that will allow his design to function.

Graham's imagined robot, designed "to collect assignments/homework in [the instructor's] room," was outlined in detail across the four columns of his graphic organizer. Graham identified that the robot should "not interrupt learning" "should be easy and quick," and "should collect assignments in [the instructor's room]." This first column description acknowledged the rules and norms of the classroom environment as a quiet space not to be interrupted. It also emphasized that this new technology should not be an added burden to its user (the instructor). Graham stated that his robot would have a long pole for holding the assignment box/bin, and he referred to his robot as "Wilbur." This name was ultimately adopted by the group for their final robot design. Graham stated that his robot "will be able to run code and stop at each table, should be a friendly presence with a face to encourage the turning in of homework." Again, Graham attended to the culture of the classroom. Graham also noted in his ideas for robot design that his robot should have a cover for its computer screen, and that it needed to be "a little taller than a table or student desk." Here, Graham attended to the limitations of the technology components (need to be protected) and to the physical space that the robot would need to navigate to perform its task. In his responses to column 2 in his graphic organizer, Graham touched on components, mechanisms, and phenomena. In his sketched ideas, we see many traces of this group's final product. Graham listed his "need to knows" as "how to code a stop button, how to build a safe way to house assignments, and make the robot seem as nice as possible."

[**Fig. 7** Graham's orthographic drawing]

With this list, Graham highlighted the technical (a stop button), the mechanical (coding) and the social/phenomena (how the robot will interact with humans in the space). Graham addressed action items by stating that he needed supplies to "build Wilbur from the ground up," "time to code," and "time to detail Wilbur." This attention to time connects nicely to the iterative nature of the engineering design cycle students are working through. In Graham's orthographic drawing (Figure 7), we see further attention to technical components (height, "assignment bin," "support pole," "computer box") and social components and personalization (naming the robot Wilbur and the inclusion of a "mohawk").

Group Orthographic Drawing

Following the completion of individual design drawings, graphic organizers, orthographic drawings, and play-doh prototypes, the whole class participated in a Gallery Walk [26]. This experience gave students the opportunity to lay out all drawings, models and written artifacts they'd created in support of their design ideas, and to receive feedback from peers outside of their groups. This feedback (recorded on structured forms) could be used by students to make changes to their designs. Each group was charged with coming to a consensus on a design to build.

[**Fig. 8** Group 3 orthographic drawing]

In Figure 8, we see the design drawing submitted by Group 3. The group stated that their robot would be used for handing out and receiving books. The drawn design appears to mirror Jack's individual design drawing. Despite the overlap of this submitted drawing and Jack's initial drawing, Group 3's final presentation included several aspects of Graham's brainstorming work (collecting assignments, the button used to stop at each table). How did the group come to integrate these elements? What pushed them towards the social orientation they ultimately took up? To explore these questions further, we move to Group 3's interaction as they made decisions about their group design, selected the materials they would use, and constructed their robot.

"What are we gonna do?": Narrowing the design

Following the Gallery Walk experience, all four groups were given a budget and worksheet for recording a list of materials needed to build their robot designs. Students were allotted $50 to work with, and they were presented with a price list that included available materials (e.g. poster board, glue guns, custom laser cutting services). Students were allowed to bring items from home for free, and they were required to provide reasoning for any custom 3D printing or laser cutting commissioned from the research team. Students were tasked with coming to consensus on a shared group design and creating a final materials list for this design.

In the exchanges that follow, we see how Group 3 used material and budgetary constraints, as well as the perceived technical difficulty of each individual design to inform their decision making process. They moved from attending to components and mechanisms in their individual designs to phenomena as they worked towards their shared group design. Shortly before this first exchange, Jess structured group problem solving by asking the group to make a decision about materials. Jerry offered a response in terms of the materials needed for his individual design, which featured a large hand. Graham solicited further detail by asking how the hand would operate (addressing mechanism level design concerns). As the group considered Jerry's designed hand, they recognized the time and financial constraints involved, eventually ruling the hand out of their group design. In their exchange about the hand, Graham raised a learning issue—how would the group get the parts of the robotic arm to move? This learning issue demonstrated attention to mechanism—what parts do we need and how will the parts work together? Jerry provided an abstract response, noting that "wires" would be needed, and Graham fleshed this out—proposing that cardboard pieces could be used to create a three dimensional finger. Jess brought in the added constraint of their budget. With these constraints foregrounded, Jerry proposed that they eliminate the hand from their shared design.

At this point, the group used material, technical, and fiscal reasoning to justify their choice to *not* include a key piece of Jerry's design. They brainstormed at component and mechanism levels ("hand" and "wires"), and all group members offered contributions to this decision. The group moved forward with their decision making process—looking for ways to successfully merge their individual design ideas. Their discussion focused for a while on design materials needed and their cost, as well as the time and effort needed to implement the designs. Here, Jess reoriented the group to the larger phenomena and how their robot would work as a *human-centered* robot in their classroom environment. A facilitator came to the group to ask about their selected robot's purpose. After a short description by Jack of a pulley system that could be operated manually to lift books up and down, Jess pointed out; "So basically, our robot that's supposed to do stuff for us, we're doing for it." This point prompts Graham to explain that the robot could simply travel to each table to collect books rather than moving them up and down. Jess responded; "So it's basically just like, a box." With this summary, Jess highlighted that manually operating a pulley system defeats the purpose of automating book collection through the use of a human-centered robot. This demonstrated an awareness of the human environment and how to design for it (phenomena). Jack and Graham continued to negotiate which of their design ideas would be taken up at the group level. At this phase, the group abandoned their pulley system. Jess chimed in with an alternate proposal that moved beyond the "walking box," but was not as complex as the pulley system proposed by Jack:

Jess: (overlapping) We could do like, tiny squares.
Graham: Tiny squares? Oh like, little boxes? Boxes on boxes? …Wouldn't it be cool if you could take them off too?

This interchange of ideas speaks to the drawn box design included at the bottom right hand corner of Group 3's submitted design drawing (Figure 9). Here, we see Jess' idea to include multiple boxes instead of a pulley system represented. The group has attended to this idea as reasonable within their budget (they can bring boxes from home) and as less technically complex than the original pulley system.

[**Fig. 9** Group 3 design drawing]

In the above exchanges that occurred throughout Group 3's selection of a cohesive robot design and creation of a materials list, we see the themes and connections made in their final presentation emerge. As all four group members considered the technical, financial, and task-oriented constraints of constructing their robot design, they moved between component, mechanism, and phenomena levels. From these brief interactive moments, we see how the group progressed from Jack's book carrying design to a hybrid final design assignment collection and a creative stability system. In the following episode, we see how the group continued to move between the technical and the social as they engaged in the construction of their robot design.

Wobbles and stability: The physics of balance

Following Group 3's design brainstorm and early "build day" experiences, the group's robot emerged as a teacher's assistant—passing out papers to students in small groups. As the group built and tested their robot, they recognized an issue with stability. Their robot continued to tip as it got close to the table where it was meant to collect assignments—wobbling beneath the weight of the laptop placed on its top. As the three boys in the group debated how to use a skein of yarn to solve the problem, Jess jumped in with an idea to poke holes in the base and the top of the cardboard robot body and thread the yarn through them—pulling tight to balance the body. Graham championed Jess' idea and began to carry it through. The rest of the group followed suit and was happy with the result. A facilitator in the room commended Jess for her idea, and Jess admitted "yeah, I felt pretty good about that." Jerry began to test the weight of papers their robot could hold, and the group reflected on their work—commenting on the balance principles they uncovered.

Jerry: All the pressure is on this right now.
Graham: Yeah, all the pressure-
Jack: (overlapping) So you need to make sure it's tight.

Here, the students were attuned to the technical. Acting on Jess's idea to weigh down the front by attaching strings, they discovered their robot was much more stable. Jack provided reasoning: "All of the pressure is on this right now," referring to the string. The group successfully used science knowledge to improve their design. They went on to test their robot's path again, after it nearly hit another student standing in the way. Despite their path being more successful this time around, Jack stated "We'll adjust that" multiple times, indicating his attention to iterative work and the technical coding aspect of the robot. Meanwhile, Jerry mimed putting papers into the robot, reflecting its social function. The facilitator and tech facilitator directed attention to the social by asking questions and interacting with the students.

Discussion

Our descriptions of final student projects above, and the iterative design process through which the groups developed their final designs, show that students were able to use our HCR curriculum to attend to both the technical and social aspects of robotics. The focus on providing a benefit to the local school environment allowed students to start their work from a space they were familiar with and to demonstrate their understanding of designing for specific social environments. We see evidence of this understanding in the kinds of locally specific functions students chose (e.g. helping a teacher, collecting trash) and the ways they incorporated the culture and social dynamics of the classroom into their designs. While students could move between social and technical considerations in their designs, they struggled to consider both simultaneously. This is a common occurrence in robotics design more generally – while robotics often aims to provide societal benefits, the technical complexity of constructing and programming robots commonly results in a technologically deterministic focus in robotics development, in which social benefits are expected to result from technical advancement without specifying the exact mechanisms of this connection [13]. In this sense, the difficulties students experienced in connecting the social and technical aspects of robotics can be seen as authentic to the problem space. Further iterations of our curriculum will involve developing further scaffolding activities for engaging students in sociotechnical learning through design. This could include making sure that students experience at least one user testing cycle, which several groups did not do due to lack of time in the semester.

Despite the authentic challenges students experienced in connecting the social and technical, using a problem-based approach and human-centered application domain for design gave students ample opportunities to think through hardware design, programming, and the socially beneficial use of technology from different perspectives. Students explored the physical properties of the materials they were using, considered the interconnections of technical, fiscal, and social costs and benefits of different design options, and discussed how people might respond to having their robot in the environment. As seen in our examples, human-centered robotics is particularly well suited for supporting this kind of problem-based learning because the functions robots are expected to perform are inextricably linked with the social environment and people's needs, attitudes, and responses to different robot designs. The diversity of concerns and approaches that students could take, as well as the open-ended nature of the problems they were solving, also supported an epistemologically pluralistic learning context. Students negotiated which approach was appropriate for solving the problem and what to focus on in design. This setting also emphasized the social nature of learning and of STEM work, which relies on communication and interaction with other people.

Our examples show that most of the groups participating in the class were motivated to actively participate in HCR design, and to connect it to different areas of their own interest and concern (e.g. hardware design, providing assistance to people). Male and female students alike took part in the activities, and emerged as discussion and design leaders at different times in the project. Our project also involved several measures of further interest development in STEM, which we do not report here.

In summary, our work demonstrates that a problem-based HCR curriculum can help students attend to and work through the connections between social and technical aspects of emerging technology design. This opportunity prepares students to recognize the interconnections between the technical and social as components of a larger system, as we described in our analysis of students' work using the CMP schema. Furthermore, our curriculum shows how different types of disciplinary knowledge (physics, programming, social science, design) are all needed to produce societally useful technological artifacts. As students are immersed in and aware of the social environment from their earliest educational experiences, we expect this type of approach can be extended into earlier (K-6) and later (undergraduate, graduate) educational years. This extension might include amending the technical complexity of the work being done to fit the age group, but would keep the sociotechnical, problem-based focus of the learning activities.

Compliance with Ethical Standards

This research was funded by National Science Foundation awards DRL-1433414 and DRL-1433841.

All participants and their parents/guardians agreed to participate in this study and submitted Informed Consent forms.

The authors declare no other conflicts of interest.

References

[1] Barker BS, Ansorge J (2007) Robotics as means to increase achievement scores in an informal learning environment. J Res Technol Educ 39:229–243

[2] Weinberg JB, Pettibone JC, Thomas SL, Stephen ML, Stein C (2007) The impact of robot projects on girls' attitudes toward science and engineering. In: Robotics Science and Systems (RSS) Workshop on Research in Robots for Education. Georgia Institute of Technology, Atlanta, GA, 30 June 2007

[3] Mataric MJ, Koenig NP, Feil-Seifer D (2007) Materials for enabling hands-on robotics and STEM Education. In: AAAI spring symposium: semantic scientific knowledge integration, pp 99–102

[4] Williams D, Ma Y, Prejean L (2010) A preliminary study exploring the use of fictional narrative in robotics activities. J Comput Math Sci Teach 29(1):51-71

[5] Robinson LE, Whittier M (2007) Teaching evolution to non-English proficient students by using Lego robotics. Am Second Educ 35(3):19-28

[6] Scassellati B, Admoni H, Matarić M (2012) Robots for use in autism research. Annu Rev of Biomed Eng 14:275-294

[7] Hamner E, Lauwers T, Bernstein D, Nourbakhsh IR, DiSalvo CF (2008) Robot diaries: broadening participation in the computer science pipeline through social technical exploration. In: AAAI spring symposium: using AI to motivate greater participation in computer science, pp 38–43

[8] Qidwai UA (2007) A LAMP-LEGO experience of motivating minority students to study engineering. ACM SIGCSE Bulletin 39(4):41-44.

[9] Schaal S (2007) The new robotics: towards human-centered machines. HFSP Journal 1(2):115-126

[10] Baker D, Leary R (1995) Letting girls speak out about science. J Res Sci Teach 32(1):3-27

[11] DiSalvo C, Nourbakhsh I, Holstius D, Akin A, Louw M (2008) The neighborhood networks project: a case study of critical engagement and creative expression through participatory design. In: Proceedings of the 10th conference on participatory design, Indiana University pp 41-50

[12] Gomoll A, Hmelo-Silver CE, Šabanović S, Francisco M (2016) Dragons, ladybugs, and softballs: girls' STEM engagement with human-centered robotics. J Sci Educ Technol 25(6):899-914

[13] Šabanović S (2010) Robots in society, society in robots. Int J Soc Robot 2(4):439-450

[14] Turkle S, Papert S (1992) Epistemological pluralism and the revaluation of the concrete. J Math Behav 11(1):3-33

[15] Hmelo-Silver CE (2004) Problem-based learning: what and how do students learn? Educ Psychol Rev 16(3):235–266

[16] Hmelo CE, Holton DL, Kolodner JL (2000) Designing to learn about complex systems. J Learn Sci 9(3):247-298

[17] Kolodner JL, Camp PJ, Crismond D, Fasse B, Gray J, Holbrook J, Puntambekar S, Ryan M (2003) Problem-based learning meets case-based reasoning in the middle-school science classroom: putting Learning by Design(™) into practice. J Learn Sci 12(4):495-547

[18] Buchanan R (1992) Wicked problems in design thinking. Des Issues 8(2):5-21

[19] Blumenfeld PC, Soloway E, Marx RW, Krajcik JS, Guzdial M, Palincsar A (1991) Motivating project-based learning: sustaining the doing, supporting the learning. Educ Psychol 26(3-4):369-398

[20] NGSS Lead States (2013) Next Generation Science Standards: For States, By States. http://www.nextgenscience.org/get-to-know

[21] Resnick M (2007) All I really need to know (about creative thinking) I learned (by studying how children learn) in kindergarten. In: Proceedings of the 6th ACM SIGCHI conference on creativity and cognition. ACM, pp 1–6

[22] Castanheira ML, Green JL, Yeager E (2009) Investigating inclusive practices: An interactional ethnographic approach. Investigating classroom interaction: Methodologies in action 145-178

[23] Powell AB, Francisco JM, Maher CA (2003) An analytical model for studying the development of learners' mathematical ideas and reasoning using videotape data. J Math Behav 22(4):405–435

[24] Jordan B, Henderson A (1995) Interaction analysis: foundations and practice. J Learn Sci 4(1):39–103

[25] Sinha S, Rogat TK, Adams-Wiggins KR, Hmelo-Silver CE (2015) Collaborative group engagement in a computer-supported inquiry learning environment. Int J Comput-Support Collab Learn 10(3):273–307

[26] Kolodner JL (2002) Facilitating the learning of design practices: lessons learned from an inquiry into science education. J Ind Teach Educ 39(3)

Fig. 1 Final robot presentations

GROUP 1 GROUP 2 GROUP 3 GROUP 4

Fig. 2 Group 3

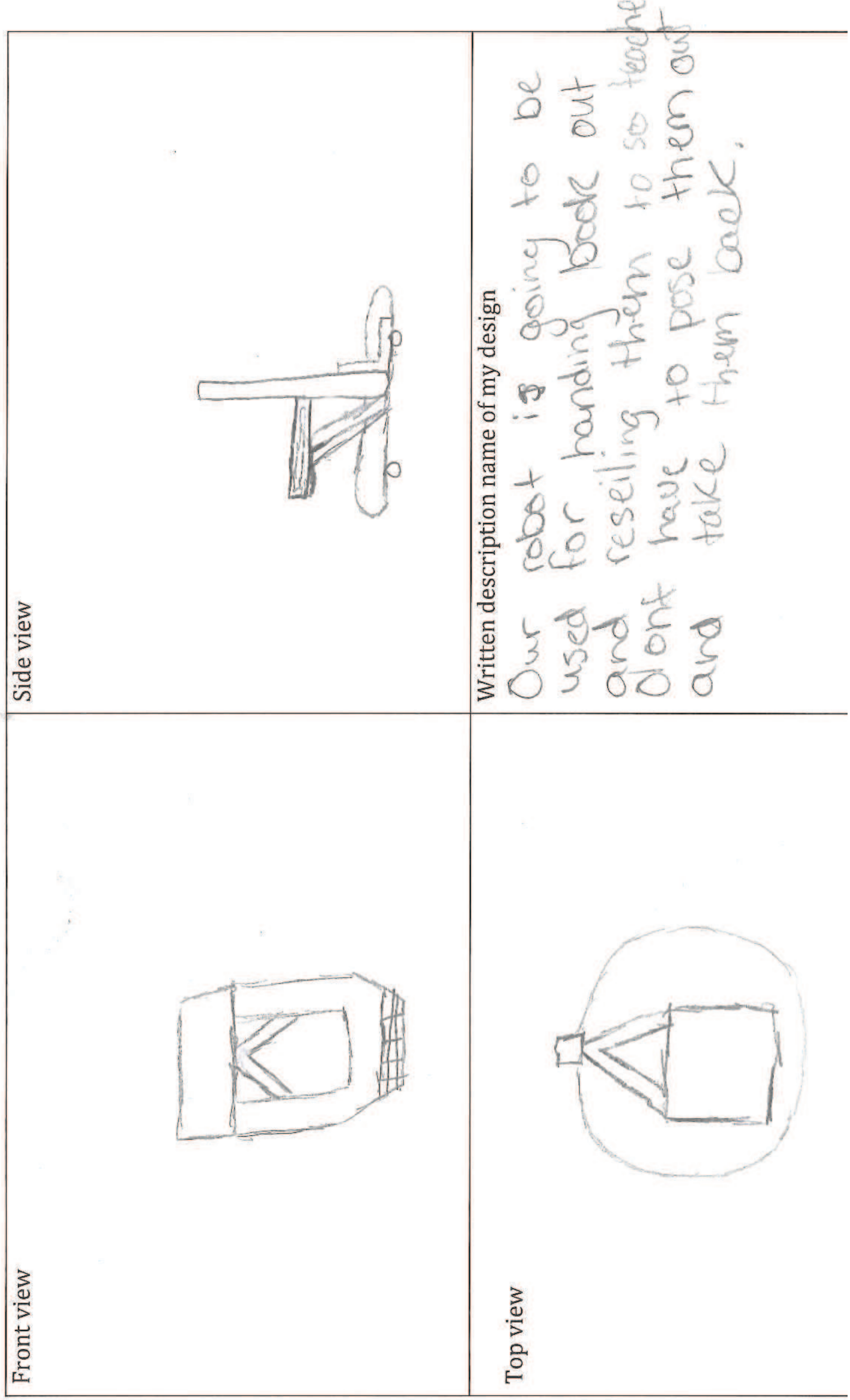
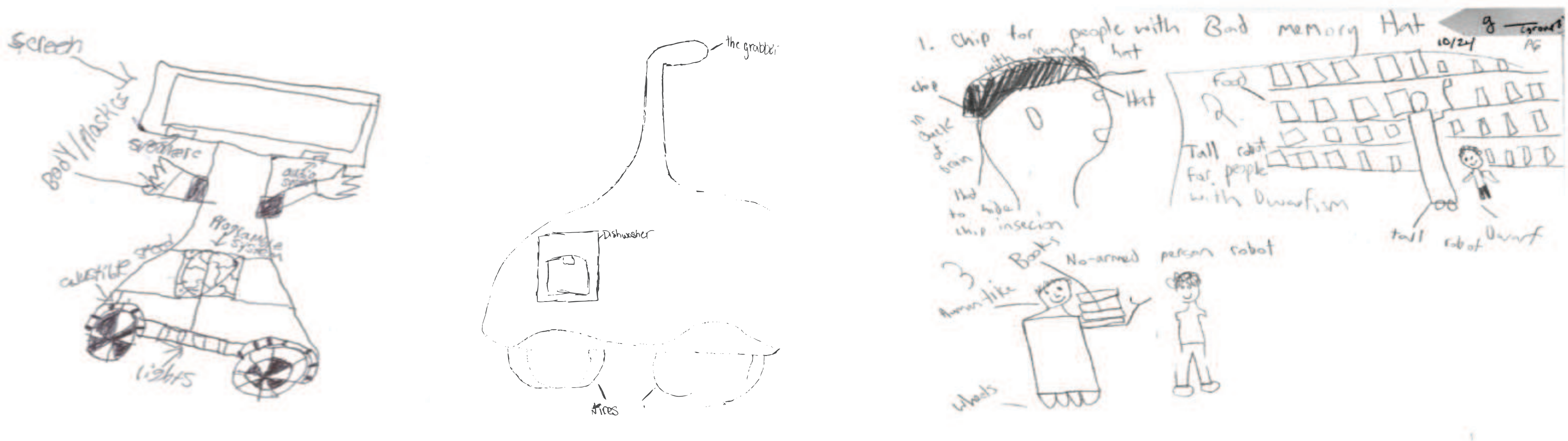

Front view
Side view
Top view
Written description name of my design
Our robot is going to be used for handing book out and reseiling them to so teacher dont have to pose them out and take them back.

Fig. 3 Group 3 early design drawings

Click here to download Figure ijsr_Fig3.eps



Jack Jerry Graham

Fig. 4 Jack's orthographic design drawing

Click here to download Figure ijsr_Fig4.eps

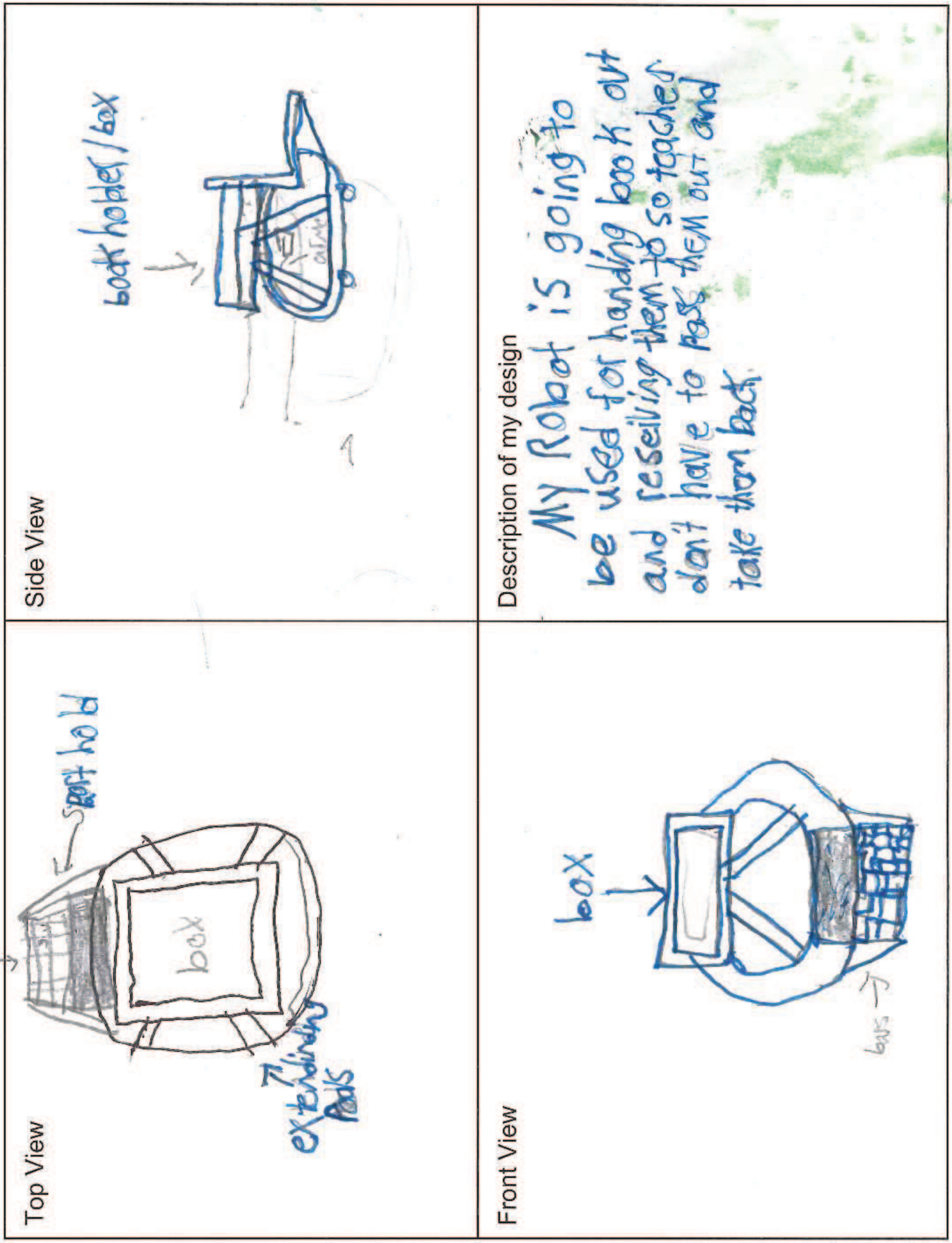


Fig. 5 Jess' orthographic design drawing

Click here to download Figure ijsr_Fig5.eps

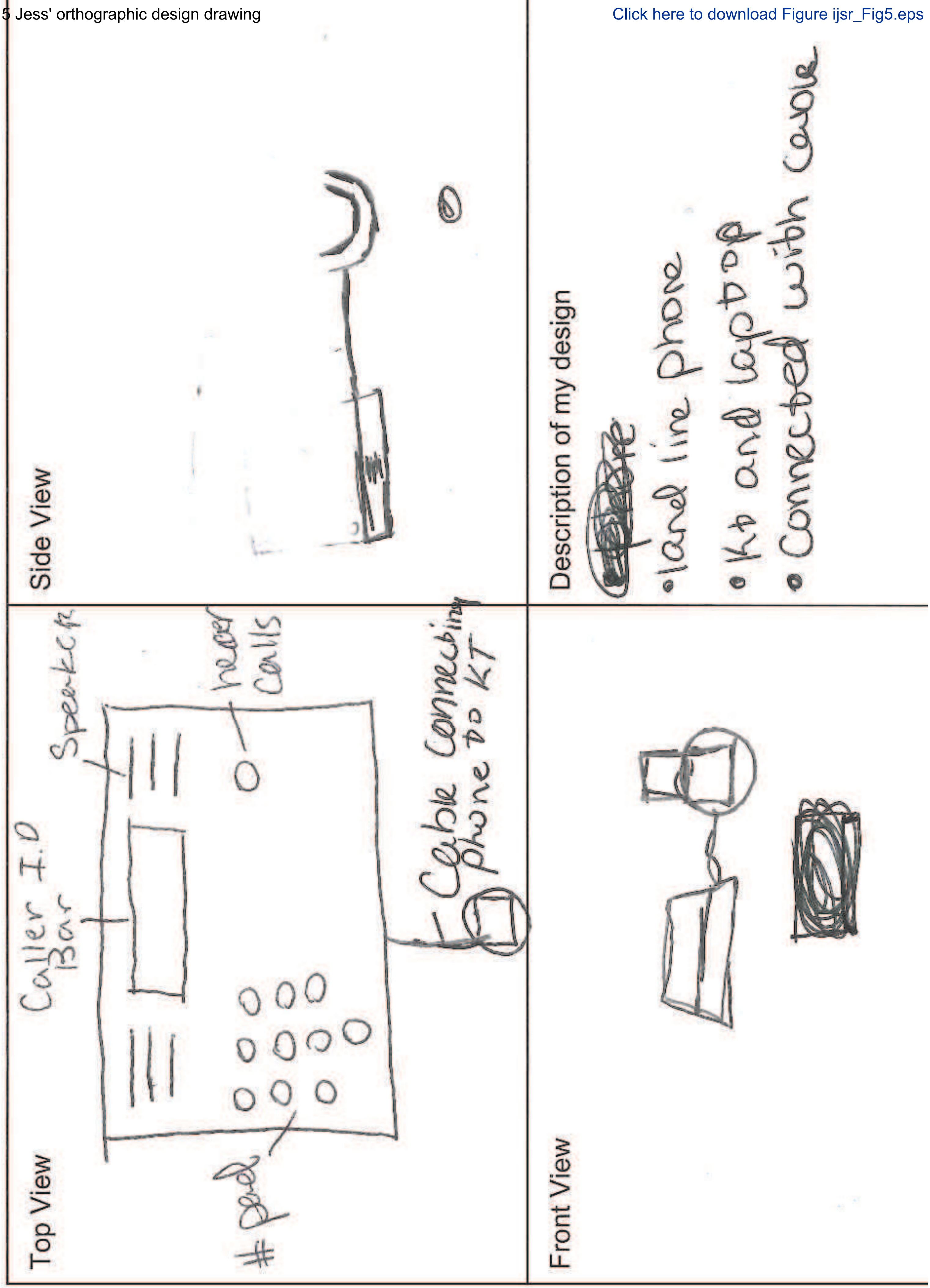


Fig. 6 Jerry's orthographic design drawing

Click here to download Figure ijsr_Fig6.eps

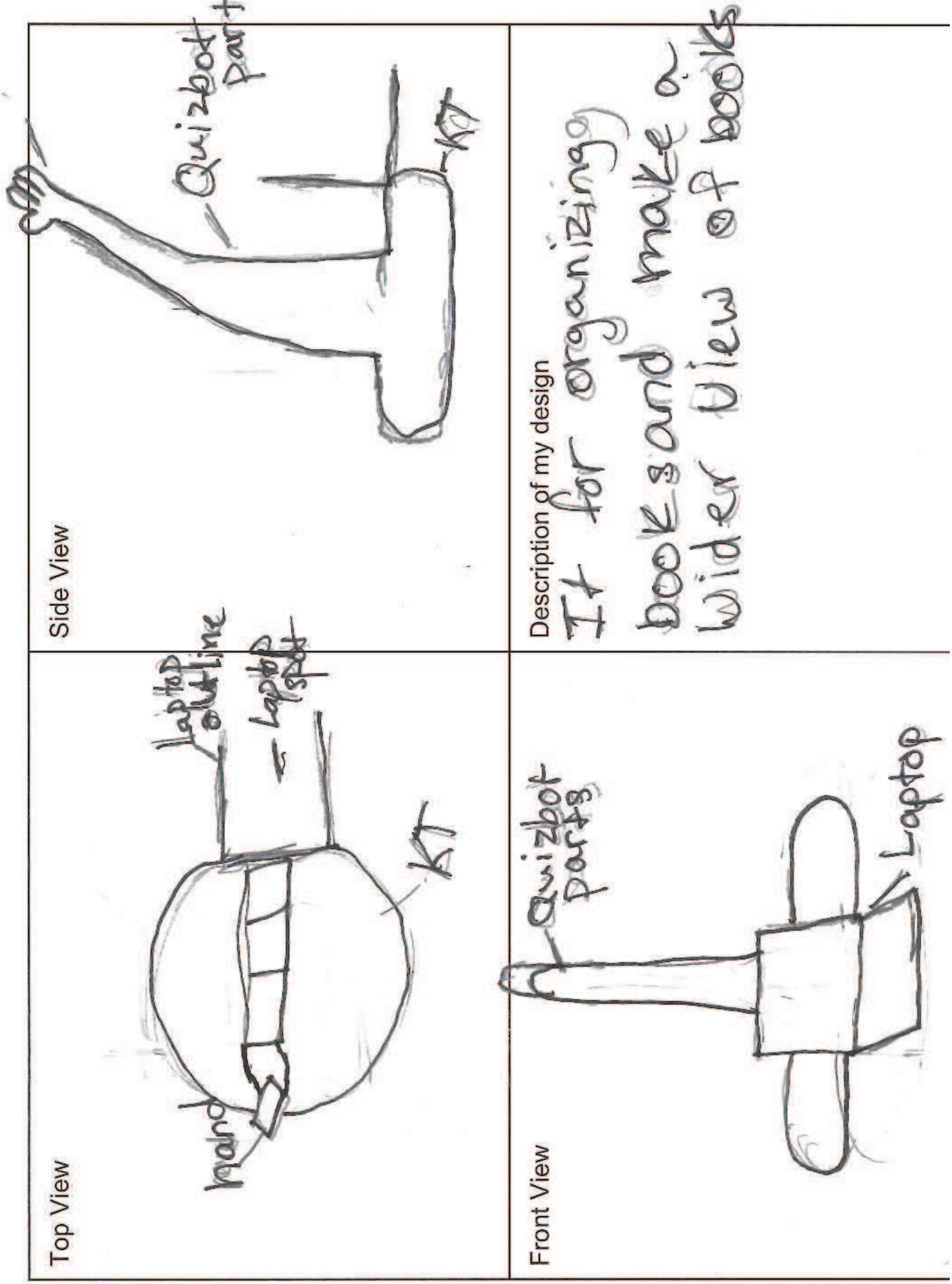


Fig. 7 Graham's orthographic design drawing

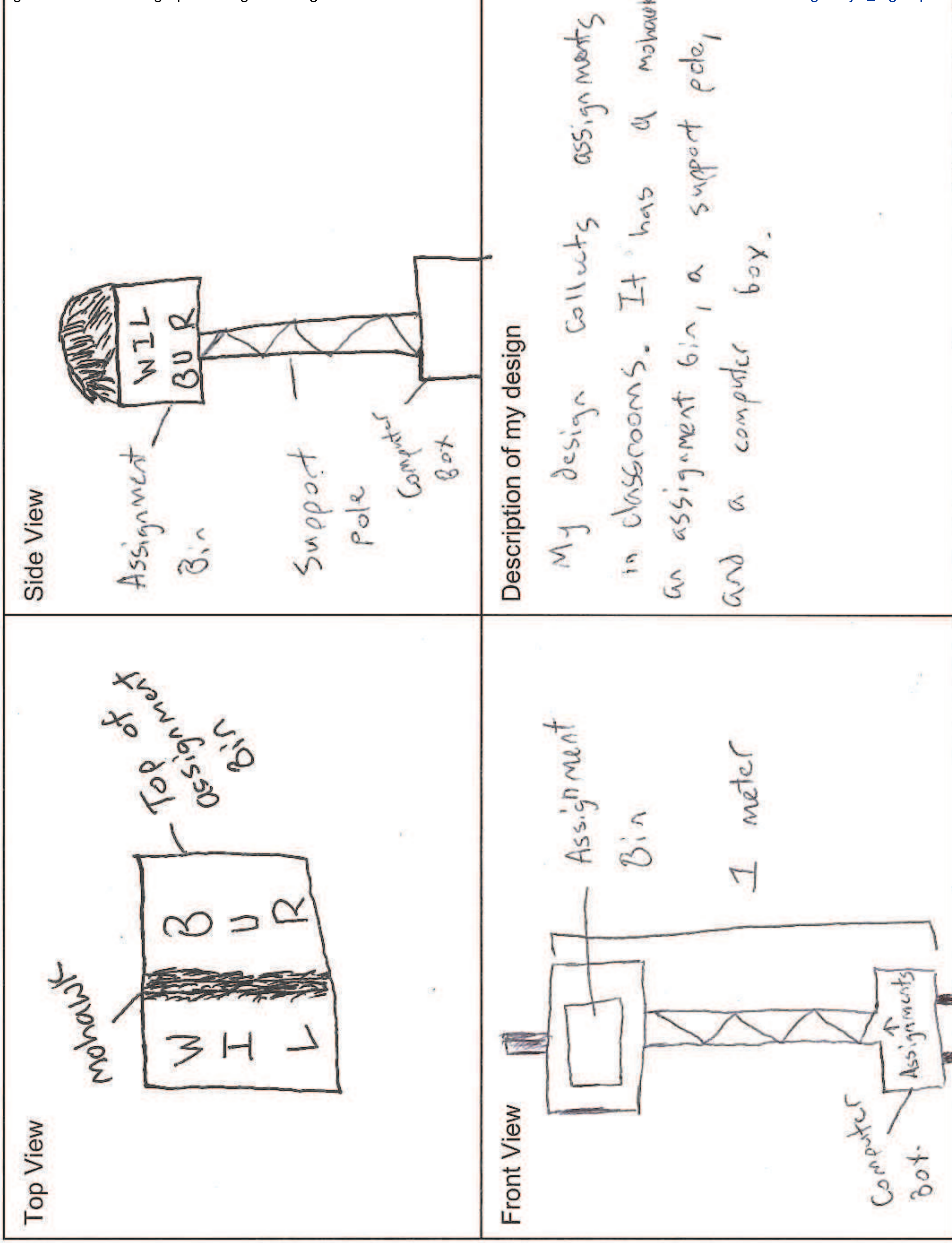


Fig. 8 Group 3 orthographic drawing

Click here to download Figure ijsr_Fig8.eps

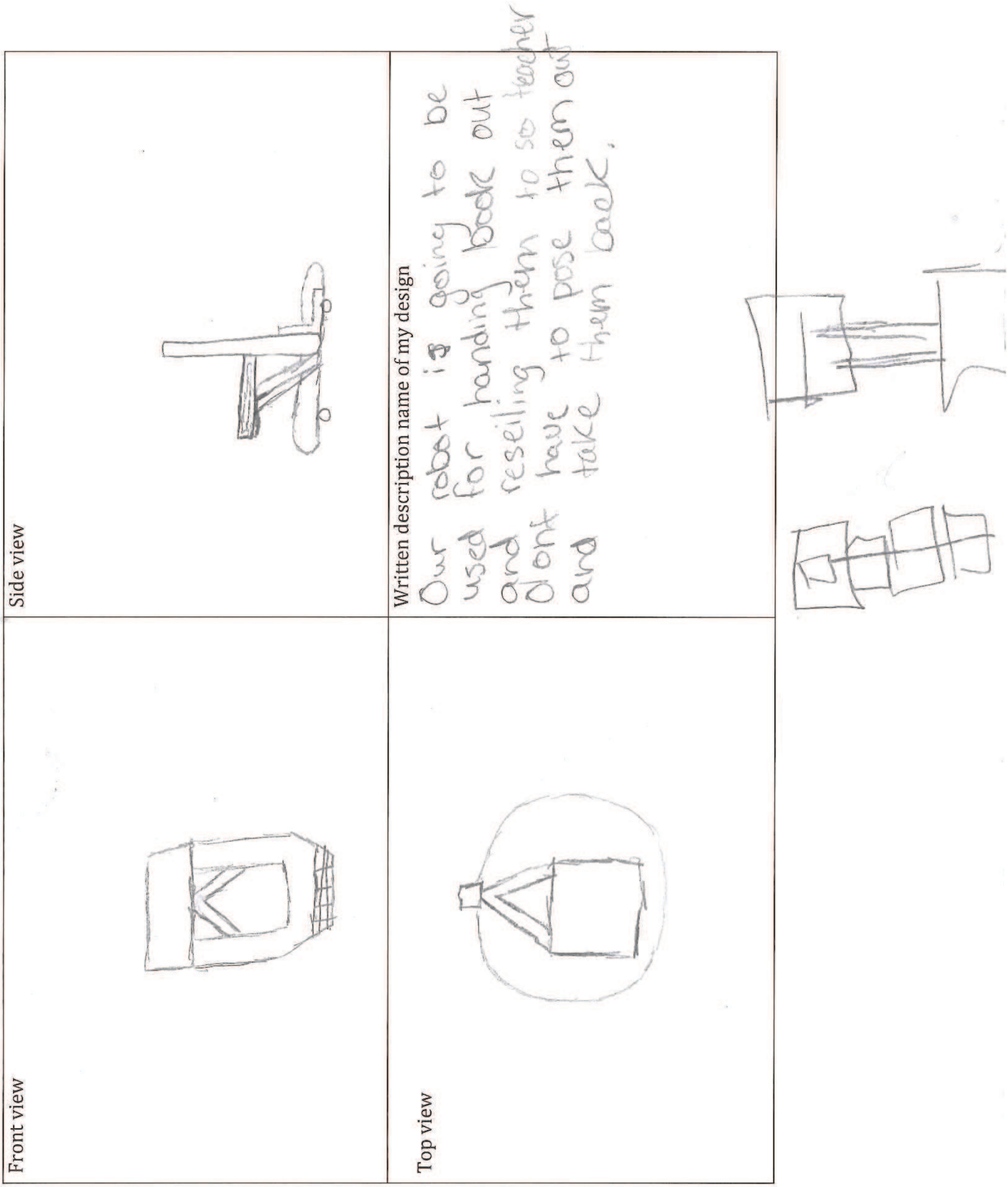


Fig. 9 Group 3 design drawing detail

Click here to download Figure ijsr_Fig9.eps

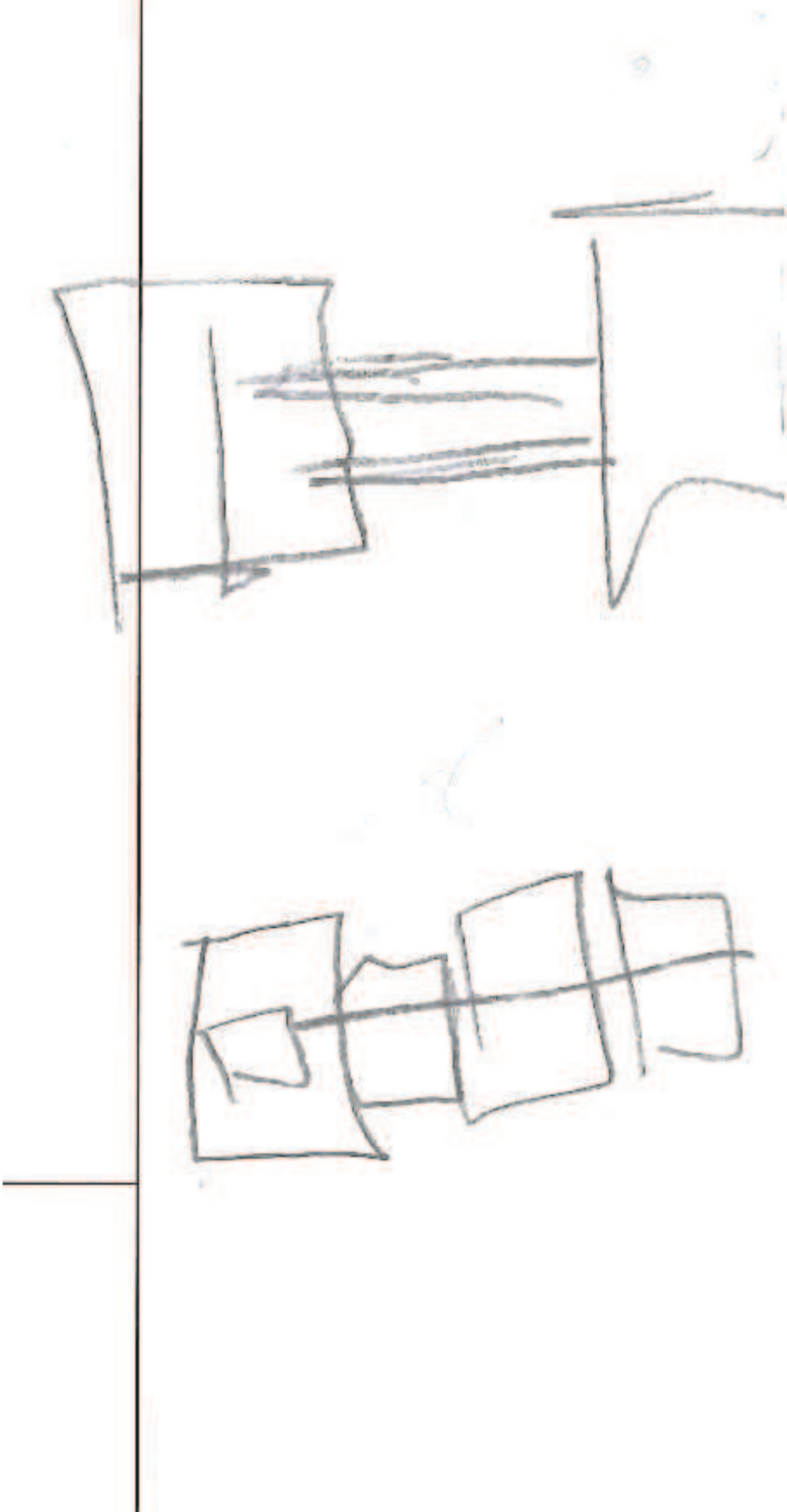


Table 1. HCR Unit trajectory

Unit Component	**Description**	**Activity details**
Brainstorming and exploring	• Interactive presentation highlighting human-centered robots • Hands-on robot stations to orient students to robotics and engineering practices, and the online learning management system used throughout the unit (Canvas) • Full class brainstorm: How can a human-centered robot serve a local need in their school • Students wrote messages to peers in Sitka, AK to meet the remote visitors who would explore the IN classroom • Re-introduction of HCR problem: Design a robot to serve a local need in your community and allow remote visitors from the partner classroom in AK to explore telepresently	Introductory stations included: • Driving an iRobot Create 2 robot around their classroom • Designing and programming a simple companion robot • Experimenting with circuitry kits • Reflecting on what "counts" as a robot and where robots exist in our everyday lives • Reading and writing about several human-centered robot articles.
Mapping	• Create maps of the classroom for the AK students to use while navigating the IN classroom using KT robots • Goal: build interest in exploring remote spaces, discover the difficulties of teleoperation in their school environment	Each group in the class selected and mapped a classroom tour for Alaskan students to take—providing reasoning for the artifacts and locations they included on their maps.
Embodied programming	• Develop a clear set of instructions that allow a student from another group to navigate the classroom • Understand the importance of clear coding directions • Improve instructions and learn from mistakes • Test the code with the KT robots	Students moved from intuitive instructions ("walk forward") to detailed instruction ("walk forward 4 steps, turn 90 degrees), to codes to input into the RobotMoose system ("forward(100), left(90)."
Designing	• Brainstorm, sketch, and model robot design ideas • Give and receive feedback from classmates • Combine ideas into one unified design per group • Select and budget for materials to build on the KT platform.	Students sketched and modeled their imagined robots and displayed them in a Gallery Walk—an experience designed to showcase artifacts and design ideas in progress [26].
Building	• Build the physical robot bodies: most groups stopped here • One group tested the robot in the space and began programming buttons related to the robot's function • Each group presented their robot and design decisions to the class.	Telepresence connections with students in Alaska occurred at two points during these build days, and students were able to have these students test out their "classroom tours" remotely, and to ask personal questions and build relationships.