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ASSESSMENT OF RELATEDNESS TO A GIVEN SOLUTION IN 3D FABRICATION AND PROTOTYPING EDUCATION

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Abstract: This study outlines initial steps to define a new framework to measure relatedness, originality and creativity of student projects in FabLab environment. A default project topic provided to students in a 3D fabrication and prototyping class served as a basis to investigate originality on the functional component level. The added components with their input and output methods, along with the control logic, were used to judge the relatedness to a given solution of the generated design ideas. An example set of ideas given by the students was evaluated with the proposed framework. The framework can complement existing measures of originality and creativity in general.

Keywords: *3D fabrication, FabLab, prototyping, interactive prototype, programming, microcontroller, Arduino, creativity assessment*

1. Introduction

3D fabrication has gained popularity recently (Strickland, 2013), and it has been widely acknowledged that combining and implementing 3D fabrication and prototyping in various education courses provides the students with an opportunity for learning and inventing new items (Carrington et al., 2015). However, for the participants in these courses, there are initial barriers to overcome, for example, in terms of confidence (Analytis et al., 2015).

To spark the imagination and creativity of the students without creating too many restrictions is a major challenge for the fabrication and prototyping courses (Carrington et al., 2015). This is especially difficult when the students have no prior experience in similar activities. Two main barriers exist for such classes: there is a barrier to prototyping with electronics (Analytis et al., 2015), and the barrier to prototyping and materializing with 3D fabrication.

1.1. 3D fabrication and prototyping education

In order to encourage creativity and overcome these barriers, it is common in 3D fabrication and prototyping education to provide an open-ended design brief. However, this may leave the students without any clue as to what is possible with regard to prototyping and experimenting in the given situation.

One approach is to provide them with an example solution and a basic set of electronic components corresponding to that solution. When such an example is provided, it may influence the creativity of the generated ideas—particularly the originality of such ideas—that often lead to design fixation (Linsey et al., 2010).
However, the question that arises is how to evaluate relatedness to a solution when a fully specified solution provides an open-ended design brief.

1.2. Creativity, originality, paradigm relatedness, and relatedness to a given solution

There is a wide variety of metrics available for evaluation of creativity (for reviews see Oman et al., 2013; Verhaegen et al., 2013). One approach is measuring creativity on the basis of two components: *novelty* and *quality* (Oman et al., 2013). Novelty has been defined as the degree to which a given design concept was unusual relative to other ideas, including those from other individuals (Shah et al., 2003; Nelson et al., 2009). Verhaegen et al. (2013), on the basis of previous research, summarize the novelty of generated ideas as consisting of *originality* and *paradigm relatedness*.
Research evaluates creativity or measures the idea effectiveness in four respects—novelty, variety, quality and quantity. It classifies the ideation measures into process-based and outcome-based approaches (Shah et al., 2003). The evaluation of creativity employs various approaches to assess novelty. The universe of ideas is used to compare and define what is not novel (Shah et al., 2003). Alternatively, Shah et al. (2003) collected all ideas generated by all participants, analyzed the ways in which attributes are satisfied, and counted the instances of each solution that exists in the entire collection of ideas, which provided evaluation of novelty. The novelty of a design resulting from a design process is evaluated with a model of causality—the SAPPhIRE model (Srinivasan & Chakrabarti, 2010).
High creativity is necessary in any design activity. We refer to the terms ‘high’ and ‘higher’ with respect to creativity. In terms of components assessing creativity, same prefixes are used—like ‘high’ originality (corresponding to ‘low’ paradigm relatedness), translating to ‘high’ novelty and ‘high’ creativity.
Comparing the originality of the generated idea with the fully specified solution can be seen as a measure of the *relatedness to a given solution* (Figure 1). Here, the notion of the relatedness to a given solution does not overlap with the notion of the paradigm relatedness component of novelty. In this case, paradigm refers rather to the degree to which the idea is radical or transformational (Verhaegen et al., 2013). An idea that scores high (high novelty) on paradigm relatedness does not necessarily score high on relatedness to a given solution. For example, an idea can use the same components in a radical new way (e.g. motor as a balance). Paradigm relatedness and originality are two components of novelty. The relatedness to a given solution proposed here can be seen as an aspect of originality. Originality expresses the degree to which an idea is not only rare, but also ingenious, imaginative, or surprising (Verhaegen et al., 2013). The relatedness to a given solution is intended to measure how original is an idea based on a single reference point of the example of fully specified solution, when provided. Therefore, it is a relative metric. Usually, originality and paradigm relatedness are evaluated on the basis of space of all relevant ideas to compare to. However, the relatedness to a given solution refers to a single relevant idea.

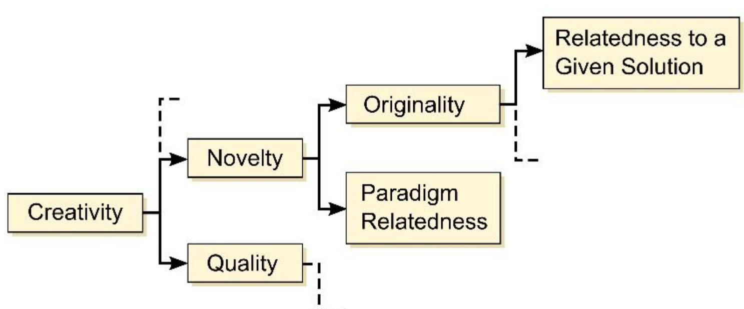

Figure 1. Place of relatedness to a given solution in the metrics for evaluation of creativity

Further, it is an outcome-based approach measuring an aspect of novelty when fully specified solution is provided. The paradigm of the solution is different from the idea exposure paradigm in design idea generation (Perttula & Sipilä, 2007), mainly because of the full specification of the solution and extensive exposure to it during the design process.

1.3. Functions and functional components

We distinguish between the functions of the generated ideas and the functional components for realization of these ideas. Functions and functional basis are originally derived using electro-mechanical designs (Campbell et al., 2000; Chakrabarti & Bligh, 2001; Hirtz et al., 2002). Usually, design requirements or specifications are described in the literature in terms of function, and then functions are described and manipulated (e.g. Hirtz et al., 2002; Bryant et al., 2005; Fu et al., 2013). The requirements or specifications are generally supplied prior to the conceptual design phase. The 'function' is placed between these and the products that are designed. Requirements or specifications are usually described in terms of function and are suggested as a 'desired function' (Chakrabarti & Bligh, 2001; Goel, 2013).
Owing to the provided fully specified solution and the purpose of providing a simplified evaluation, this study focuses on the functional components. However, it may not account for all of the differences on the software side, programming, and interface.

1.4. Aims

Focusing on the case of a given fully specified solution, this study aims to define a new framework to measure relatedness, originality and creativity of student projects in FabLab environment. The framework is developed on the basis of a course in 3D fabrication and prototyping. The framework is intended to make the assessment of projects more concrete.

2. A case of course on 3D fabrication and prototyping

2.1. Course setup

The ongoing '3D Fabrication and Prototyping' course, which is discussed in this study, is implemented in the computer science and engineering curriculum of the University of Oulu (3D fabrication and prototyping course [2016]).
This course introduces the students to interactive physical prototypes that combine mechanical, electrical, and software components. 3D fabrication and prototyping is used to create a physical object that interacts with its surroundings. The course includes reading data from sensors, controlling sensors and electric motors with an Arduino board. The students are given a set of initial components (Figure 2), including Arduino Micro board, which is based on the default project topic (explained later on). The additionally provided printed circuit board (PCB) is not shown in the picture. The aim is to elaborate electronic components and to implement control logic for Arduino with the material implementation of the generated idea.

2.2. Default project topic

The default project topic is an *alarm clock robot that starts to run away when the alarm starts to ring and user touches the device*. The default project example uses some selected components for the alarm clock project. The selected components are mentioned in the following:

- Gyro and accelerometer sensors are used to observe the random movement of the device.
- Buzzer (i.e., the piezo element) is used to signal wake up time (LEDs can also be used).
- The motor enforces physical random movement through the motor controller component.
- When a real time clock is used for the wake-up call, serial communication must be used to set the (approximate) time for the clock timer.

The students are encouraged to propose ideas for interactive prototypes different from the default topic.

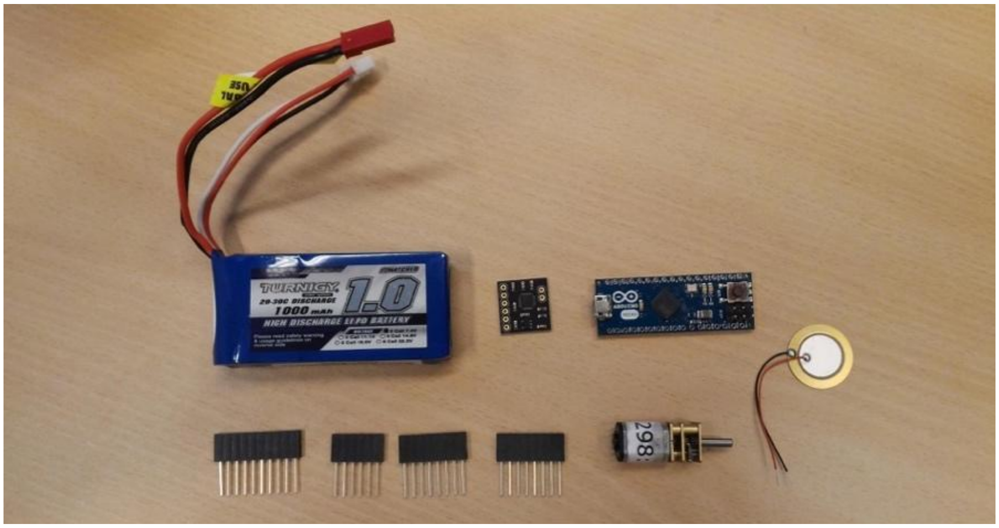

Figure 2. Initial components given to the students
(top from left to right: battery, gyro and accelerometer board, Arduino Micro board, and piezo element; bottom: four types of connectors and motor)

3. Framework for the assessment of relatedness to a given solution

3.1. Analysis of components

Table 1 shows the initial functional components with the corresponding input method, output method, and control logic. The input or output methods corresponding to the provided default project topic are marked with *. For example, the default project uses the piezo element as an output method for audio transducing (buzzing alarm sound). However, the piezo element can also be used as an input method for detecting a vibration or a knock. Furthermore, the column of control logic attempts to account for the software level of the generated ideas in a general way.
Here, control logic is defined according to the way in which the concrete function is governed. For example, the motor can use systematic or random control logic. In the default project, the control logic of the motor was random in order to make random movements. In addition, there are different ways to achieve the same result. For example, instead of using software to create random movements (see Table 1), it is possible to achieve this with device instability. The comparisons and analyses are made on the basis of used components, their input and/ or output methods, and control logic.

Table 1. Initial functional components with corresponding input and output methods, and control logic

Component	Input method	Output method	Control logic
Gyroscope and accelerometer (three-axis gyroscope and a three-axis accelerometer)	*Precisely and accurately tracking motions		*Hardware interface or software libraries or own custom software
Piezo element (buzzer)	Detecting vibration or a knock	*Audio transducing (buzzing)	
Motor (micro gearmotor)		*Rotating	Systematic or *Random
Battery		*Voltage current	

3.2. Criteria and representations

The suggested framework uses the criteria proposed and summarized in Table 2. The generated ideas are rated on the general feature level in comparison with the default project topic. The criteria in Table 2 are scored with low originality (L) or high similarity, when more default functional components or suggested alternatives in the design brief are used. This is the case when the used functional components are close to the default topic. The criteria are scored as medium originality (M) when the input/output method or control logic is different. Furthermore, new functional elements are scored as high originality (H) or low similarity, which is desirable from the point of view of design education. When one of the default functional components is omitted, the assessment takes place in the view of other criteria.

The analysis is done by examining the idea on all of the criteria mentioned in Table 2. Then, the total score is assigned by counting all the individual scores. For example, an idea can be scored as H2M1L1, which means that it has two functional components scored as high originality, one medium, and another low. Afterwards, the ideas can first be compared by the number of H scores, then by the number of M scores, and finally, by the number of L scores.

Table 2. Criteria for the assessment of relatedness to a given solution based on the default project topic

Default project topic	Criterion	Example	Scoring
An alarm clock robot that starts to run away when the alarm starts to ring	Omitting one of the default functional components	Omitting gyroscope and accelerometer	N/A
	Using more than one default functional components	Using additional motors	Low originality (L)
	Using functional components suggested in the design brief but not present in the default project topic	Using LEDs (see Section 2.2)	Low originality (L)
	Same default functional component using different input/output method	Using the piezo element to detect vibration	Medium originality (M)
	Same default functional component using different control logic	Using motor for systematic movement (see Table 1)	Medium originality (M)
	New (added) functional element	Adding microphone	High originality (H)

4. Example analysis of student ideas

In this section we explore and assess the relatedness to a given solution of the ideas of interactive prototypes according to the above framework. The formulated ideas of the students, halfway of the course, were as follows:

- *A light-evading robot (moves away from light)*
- *A custom lid for a water boiler (replacement lid for a water boiler, which uses a winch to lower a brewing ball into the water when it is the correct temperature and then pulls it up after a certain amount of time)*
- *A drink pouring holder (a holder for a wine bottle, which will replace the cap with a valve; when a button is pressed, it pours wine into a glass; a sensor will be used to measure the amount of wine poured)*
- *A wheeled alarm tube (a cylinder with wheels at the ends)*
- *An alarm tank (an alarm bot on tracks, has a forward-facing sonar sensor to avoid obstacles)*
- *A two-wheeled robot (moving in high speed using large hoop wheels)*

- *A ping pong ball catapult (it has two actuators activated by buttons—one to rotate the arm that throws the ball and the other to rotate the base for aiming)*

One first example of student idea is *a light-evading robot*. When the robot is lighted by strong light—for example, a flashlight—it tries to evade it and move to a darker area. The example assessment of the relatedness to the given solution of this idea is shown in Table 3.

Table 3. Assessment of the relatedness to the given solution of idea of *a light-evading robot*

Original component (according to criteria in Table 2)	Corresponding function	Control logic	Scoring
Lights sensor (photoresistor)	Detects light	Systematic	High originality (H)
Motor (micro gearmotor)	Rotate	Systematic	Medium originality (M)
		Assessment to relatedness to the given solution	High originality (H1M1)

Another example of student idea is *a custom lid for a water boiler* (tea is submerged in water using a winch once the water is at the defined temperature and lifted up again once the tea is brewed for the set time duration). The example assessment relatedness to the given solution of the second idea is given in Table 4. The score for all is assigned as an overall assessment.

Table 4. Assessment of the relatedness to the given solution of idea of *a custom lid for a water boiler*

Original component (according to criteria in Table 2)	Corresponding function	Control logic	Scoring
Thermometer	Detects temperature	Systematic	High originality (H)
Winch	Pulling or lifting thing	Systematic	High originality (H)
		Assessment of relatedness to the given solution	High originality (H2)

Table 5 systematizes the scores of all of the student ideas. However, some of the ideas are not detailed enough.

Table 5. Assessments of the relatedness to a given solution of the rest of the ideas

Ideas	Original components	Corresponding functions	Control logic	Overall assessments of relatedness to a given solution
A light evading robot	Light sensor, motor	Detect, rotate	Systematic	High originality (H1M1)
A custom lid for a water boiler	Thermometer, winch	Detect, pull	Systematic	High originality (H2)
A drink pouring holder	Valve, button, sensor	Regulate flow, control, detect	Systematic	High originality (H3)
A wheeled alarm tube	none	none	Random	not original
An alarm tank	Sensor	Detect	Systematic	High originality (H1M1)
A two-wheeled robot	none	none	Random	not original
A ping pong ball catapult	Actuators, buttons	Rotations, control	Systematic	High originality (H2)

5. Discussion

The provided example analysis of ideas and their assessment of relatedness to a given solution in the context of the 3D fabrication and prototyping class shows a simplified assessment by comparing the generated idea with the default project topic and solution. While this assessment cannot substitute the more elaborated metrics of originality (Oman et al., 2013; Verhaegen et al., 2013), it can complement and, most importantly, provide a simple way to categorize creative ideas into groups when a default solution is present.

As an implication, the framework is applicable as a method for evaluation, which makes the evaluation more concrete. This evaluation can be used in grading the generated ideas, although it does not entirely indicate what has been learned in the course.

Beyond such an assessment, concepts could be compared for similarities or differences based on not only the novelty of components, but also, their fabrication method, intended audience, relative size, complexity, etc. Such a comparison would provide a more comprehensive answer to what exactly makes an idea similar to or different from another.

The study has general limitations. It tackles specific case of design education with a specific framework and approach.

Students may have a tendency to go with what they are comfortable with based on prior experience. This aspect should be taken into account in further work, possibly by also evaluating relatedness to a given solution to solutions or products that students have previously designed.

Furthermore, the framework can be extended to account for the complexity of the ideas/solutions and a better overall assessment of novelty. That is to say, the framework does not account for the originality on the general (complex) idea specifications level and beyond the individual functional components that are chosen to realize these specifications. It is possible that the ideas with the same set of functional components are very different in terms of overall creativity.

The following aspects have to be further considered:

- Influence of the number of the provided components
- Influence of the provided details of the default project topic
- Time of the introduction of the default project topic to the course
- How adding new algorithm to utilize data can be accounted in the proposed framework and evaluation (see Table 1)

We further plan to examine the confidence levels of the students during and after the class, and compare these evaluations with the results of the assessments in this study. This will be a step towards examining the applicability of the framework for what is learned in the 3D fabrication and prototyping class.

The main limitations of this study are the following:

- The framework has general characteristics; it does not explore any particular novelty of the idea/solution.
- The mechanical or software functions of the ideas were not evaluated in detail—e.g., the ideas of *a wheeled alarm tube* and *a two-wheeled robot* can further be differentiated, and may receive different originality assessments on the basis of the detailed functions of the mechanics or the software.

6. Conclusion

The project-based class of 3D fabrication and prototyping with the Arduino Micro board, as presented in this study, serves as a basis for proposing an assessment framework of the relatedness to a given solution. The framework examines the electronic components used in the generated design ideas and the way in which they are used in comparison with the default project topic for the solution provided. The assessment of student projects in 3D fabrication and prototyping compares the methods and logic used to implement the ideas. It also allows simplified categorization of creative ideas into groups.

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