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The Control Zendo: A Game of Inductive Logic for Teaching Automatic Control

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Abstract: Board games and card games have been used with some degree of success in the implementation of active strategies for education, since they stimulate problem solving and increase the learning and engagement of the students. This paper shows how the mechanics of the popular game Zendo have been adapted to teach elements of a basic automatic control course at the University of Stavanger. The result is the Control Zendo, a game of inductive logic in which a hidden rule related to different system's properties (e.g., linearity, time-varyingness or number of input and output variables) must be guessed. Implementational issues and the feedback received by the students who played the game in Spring 2022 are discussed.

Keywords: Control education, educational games, logic game, pattern recognition

1. INTRODUCTION

Automatic control courses are part of the standard curricula of many engineering programs, such as electrical, mechanical and aerospace, just to name a few. Unfortunately, these courses are considered challenging by many students due to the complex and highly theoretical/abstract content of this field so strongly grounded in mathematics. It is known that complementing the traditional lectures with activities that stimulate problem solving is beneficial for the learning and engagement of the students [Knight and Wood, 2005]. For this reason, in recent years many researchers have proposed different active learning elements that can be incorporated in an automatic control course.

A possible approach to active education is the use of digital tools. In this respect, the most popular software in automatic control is MATLAB [Koch et al., 2020]. Recently, integrated development environments such as Sysquake have been successfully used to develop interactive tools to teach different concepts, such as sliding mode control [Costa-Castelló et al., 2018] or H_∞ design [Díaz et al., 2020]. Among other adopted alternatives, one can mention the use of virtual and remote laboratories [de la Torre et al., 2020] and educational video games [Munz et al., 2007].

Another possible tool for active education consists in board games and card games, which have been used with some degree of success by educators around the world. For example, Mavroudi et al. [2022] presented the design, implementation and evaluation of a card game that aims to support technology-enhanced learning activities in higher education. A comprehensive review of 29 card and board games used for medical education is available in Bochennek et al. [2007]. On the other hand, Denning et al. [2013] designed, produced, and evaluated the effectiveness of a recreational tabletop card game created to raise awareness about computer security and alter perceptions regarding it. The list of subjects for which board games have been proposed is quite long, comprising genetics [Osier, 2014], economics [Shanklin and Ehlen, 2017] and political science [Bridge, 2014], just to name a few. However, to the best of our knowledge, no board games have been proposed so far to teach concepts related to automatic control.

Zendo is a game of inductive logic designed by Kory Heath in 1999, in which one player (the *Master*) has to guide the other players (the *Students*) so that they can correctly guess a secret rule. In the original game, this is done by building and studying structures that may or may not satisfy the secret rule, using a set of game components comprising pyramids, wedges, or blocks, that come in different colors, such as blue, red, or yellow [1]. For example, a secret rule might be: *A structure must contain exactly two pyramids.* Based on the original Zendo game, DeOrsey et al. [2021] proposed a logic game that gives a fun opportunity to explore different types of mathematical objects, such as numbers and polynomials. This game has secret rules such as *The number is divisible by 3* or *The polynomial of degree* ≤ 3 *has three distinct roots.* The testing of this game was very positive, with 97.6% rate of positive feedback given by the students, along with numerous positive reviews coming from teachers and administrative staff who participated to the testing of the game as well. However, in spite of what we think is the huge potentiality of the game, there are no further reports in the literature concerning applications of Zendo to education.

Motivated by the above discussion, the goal of this paper is to show how a variant of Zendo, referred to as *Control Zendo* has been implemented and tested in the Spring 2022 basic automatic control course at the University of Stavanger, Norway. Our experiences with the game are discussed and supported by a critical analysis of the available quantitative

[1] The interested reader is referred for more information to https://boardgamegeek.com/boardgame/6830/zendo

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data about the students' opinion, which was collected through a questionnaire.

The paper is structured as follows. The course is briefly described in Section 2. A thorough description of the game rules is provided in Section 3. Section 4 provides an example of gameplay. Section 5 is devoted to the experiences with the boardgame and the discussion of the quantitative data. Finally, Section 6 summarizes the main conclusions.

2. THE BASIC AUTOMATIC CONTROL COURSE AT THE UNIVERSITY OF STAVANGER

The educational game presented in this paper has been used in the course *ELE320 - Control Systems* at the University of Stavanger, Norway. The course is part of the curricula of the Bachelor in Control Engineering and Circuit Design and the Bachelor in Energy and Petroleum Engineering. Most of the about 100 attendees are second year students.

The course corresponds to 10 ECTS credits with a total expected student workload of 250 hours. The course covers five different topics:

(1) Modelling of dynamical systems
(2) Analysis in the state-space domain
(3) Analysis in the Laplace domain
(4) The frequency response
(5) Introduction to feedback control design

and is implemented using different instructional teaching tools:

- **Asynchronous pre-recorded lectures:** the students are given each week pre-recorded lectures consisting of videos with a usual length between 10 and 30 minutes, although exceptions to this rule are made when deemed convenient;
- **Synchronous Kahoot!'ified lectures:** each week there is a 2-hours long lecture which uses a Kahoot! quiz to revise the content of the pre-recorded videos of the previous week;
- **Homework assignments:** individual assignments that contain problems related to the content covered in the lectures. These assignments contain a mix of traditional lectures to be solved *paper-and-pen* (+calculator), MATLAB/Simulink exercises and open questions that incorporate the ready-to-use simulators developed by UNED [Guzmán et al., 2012];
- **Laboratory assignments:** the students use physical equipment available at the university (a two-tank system [Stokka et al., 2017] and the Quanser Aero [2], which mimics the aerodynamical behavior of a helicopter) to solve six group-based assignments which constitute a bridge between theory and practice;
- **The Control Zendo boardgame:** this Spring 2022, the course has incorporated gaming sessions using the Control Zendo boardgame. Participation to these sessions is on a voluntary basis, but doing so counts as an approved homework assignment - the students get also free pizza out of it as well, which is a nice combo.

[2] https://www.quanser.com/products/aero-2/

3. HOW TO PLAY THE CONTROL ZENDO

3.1 Overview

The Control Zendo is a game of inductive logic inspired to the boardgame Zendo. One player acts as the *Master of the Sacred Loop*, answering to questions about the secret rule. The other players act as the *Disciples of the Sacred Loop*, taking turns in creating systems that will give them insights about the secret rule. Note that the word *player* is used to denote either an individual or a team, since there are no remarkable difference in the way the game is played between the two possible modes.

3.2 Setup

Each player receives blank sheets to write down the systems, and a sheet to write down their personal annotations. Also, each player receives two answering tokens, one black and one white. One player is assigned the role of *Master of the Sacred Loop* and receives a green and a red marker pen. It is recommended that the Master of the Sacred Loop is a player experienced with the content of the session, for example a lecturer or a high-performing student.

3.3 Summary of play

The Master of the Sacred Loop draws a card from the deck of possible rules (see, for example, Fig. 1) and marks it with the provided paperclips. It is important that the Master of the Sacred Loop understands the rule and can tell if a system satisfies or not the rule. If this is not the case, they should draw a new card from the deck. Then, the Master of the Sacred Loop writes down two systems *Sys1* and *Sys2* on their sheet. One of the systems follows the secret rule, so it gets marked with the green pen. The other system does not follow the secret rule, so it gets marked with the red pen. Then, the Disciples will take turns, each time writing down one system (*Sys3*, *Sys4*, etc.) on their sheet, finding out if it follows the rule or not, and optionally making a guess about the secret rule. However, to make a guess (and win the game if guessed correctly), the players must spend Laplace coins which are earned by correctly predicting whether a system follows the secret rule.

3.4 A disciple's turn

In their turn, the disciple must follow these steps (some of them are optional):

(1) Write down a system on their sheet (mandatory)
(2) Choose "tell" or "challenge" (mandatory, read below)
(3) Spend Laplace coins to make guesses about the secret rule (optional, read below)

Tell: If the disciple has chosen "tell", the Master of the Sacred Loop will tell whether the system follows the secret rule, marking it with the green or the red pen, accordingly (note that the sheets with the system are public information, available to all players).

Challenge: If the disciple has chosen "challenge", then *every disciple* secretly selects the white or black answering token (white if they think that the system follows the secret rule, black if they think that the system does not follow the secret rule). Then, the disciples reveal their answering tokens simultaneously. The Master of the Sacred Loop tells whether the

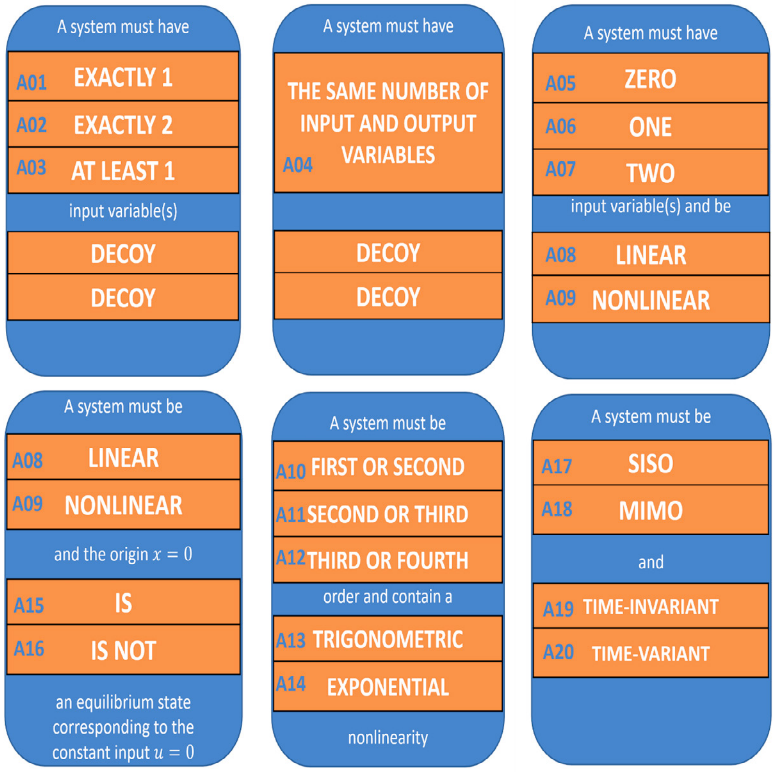

Fig. 1. *Classification of Systems* deck.

system follows the secret rule, marking it with the green or the red pen, accordingly. All the disciples who selected the correct answering token will receive a Laplace coin that can be used in their turn to make an official guess about the secret rule (possibly, winning the game, if the guess is right). The disciple whose turn is being played can immediately spend their Laplace coin, as step (3) of their turn.

Make a guess about the secret rule: As the last (optional) step in the turn, a disciple can spend one or more Laplace coins to make one or more guesses about the secret rule (one guess per spent coin). Note that a disciple can use Laplace coins that were earned in previous turns or even other players' turns to make the guess. After the disciple makes a guess about the rule, the Master of the Sacred Loop tells the disciples whether the guess is right or wrong, and in this latter case provides a counter-example that disproves the disciple's guess. Note that partially right rules are considered to be wrong.

4. A GAMEPLAY EXAMPLE

Let us simulate a possible gameplay using the deck *Classification of systems* shown in Fig. 1. We will assume a group of four students who participate to the activity, referred to as **S1**, **S2**, **S3** and **S4**. **S1**, who is the most confident in the subject, agrees to play as the *Master of the Sacred Loop*. The other three students play as *Disciples*, each of them receiving a white and black token plus blank sheets to write down the systems plus taking notes, if needed.

S1 shuffles the deck and draws the first card (rules A08, A09, A15, A16). Since the card deals with equilibrium states, which is not a clear topic to **S1**, they decide to shuffle it back into the deck and draw another card. The new card (rule A04 plus decoys) is about the number of input and output variables. **S1** feels confident enough about this to be able to manage the playing. **S1** puts two paperclip on the card, one on the rule A04 and the other on one of the decoys [3] writes down two systems, one following the rule and the other not following it, marking them with the corresponding color:

$$\begin{cases} \dot{x}_1(t) = 7x_1(t) + 4x_2(t) + 2u_1(t) + 6u_2(t) \\ \dot{x}_2(t) = 3x_1(t) + x_2(t) + u_1(t) - 3u_2(t) \\ y_1(t) = x_1(t) \\ y_2(t) = x_1(t) + x_2(t) \end{cases} \tag{1}$$

$$\begin{cases} \dot{x}(t) = 5e^t \sin(x(t)) + u_1(t)u_2(t) \\ y(t) = x(t) + 3u_1(t) \end{cases} \tag{2}$$

It is now **S2**'s turn, who wants to find out whether the hidden rule to guess could be A07+A08, as this would comply with Eq. (1) but not with Eq. (2). Therefore, **S2** writes down Eq. (3) on their sheet and chooses *Tell*, so the Master marks Eq. (3) with the red marker, as it does not satisfy the hidden rule (due to having two inputs, but only one output):

[3] All the cards are made so that there are two rules to be selected, therefore the usefulness of the decoys.

$$\begin{cases} \dot{x}(t) = 5x(t) + u_1(t) + u_2(t) \\ y(t) = x(t) + 3u_2(t) \end{cases} \quad (3)$$

In this way, **S2** (and the other players) have discovered that the hidden rule to guess cannot be A07+A08, otherwise (3) would have been marked with the green color. It is now **S3**'s turn. **S3** thinks that the hidden rule might be A18+A19, but they need a Laplace coin to make the official guess. **S3** writes down Eq. (4) on their sheet and chooses *Challenge*. Each disciple chooses secretly either the white or the black token and then they all reveal the chosen tokens simultaneously. The Master reveals that Eq. (4) does not satisfy the hidden rule, so it gets marked with the red color.

$$\begin{cases} \dot{x}(t) = t\cos(x(t)) + u_1(t)u_2(t) \\ y_1(t) = x(t) \\ y_2(t) = -x(t) \\ y_3(t) = tx(t) \end{cases} \quad (4)$$

S2 had chosen a white token, so no Laplace coin for them. Both **S3** and **S4** had chosen a black token, so they receive a Laplace coin each. Since it is still **S3**'s turn, they can spend the coin right away to make an official guess, which they do. The guess is: *a system must be MIMO and time-invariant*. However, this was a wrong guess. The Master proceeds in showing a counter-example, i.e., a system that, albeit being MIMO and time-invariant, does not satisfy the hidden rule:

$$\begin{cases} \dot{x}(t) = \cos(x(t)) + u_1(t)u_2(t) \\ y_1(t) = x(t) \\ y_2(t) = -x(t) \\ y_3(t) = x(t)u_1(t) \end{cases} \quad (5)$$

At this point, **S4** has enough information that can be inferred from the systems (1)-(5) to guess the hidden rule (see Table 1 for an overview of the information available to the players).

	Eq. (1)	Eq. (2)	Eq. (3)	Eq. (4)	Eq. (5)
A01	×	×	×	×	×
A02	✓	✓	✓	✓	✓
A03	✓	✓	✓	✓	✓
A04	✓	×	×	×	×
A05	×	×	×	×	×
A06	×	×	×	×	×
A07	✓	✓	✓	✓	✓
A08	✓	×	✓	×	×
A09	×	✓	×	✓	✓
A10	✓	✓	✓	✓	✓
A11	✓	×	×	×	×
A12	×	×	×	×	×
A13	×	✓	×	✓	✓
A14	×	✓	×	×	×
A15	✓	✓	✓	×	×
A16	×	×	×	✓	✓
A17	×	×	×	×	×
A18	✓	×	×	✓	✓
A19	✓	×	✓	×	✓
A20	×	✓	×	✓	×

Table 1. Rules vs. systems (1)-(5).

The only rules that have a ✓ × × × × sequence in Table 1 are A04 and A11, so they can be the only possible rules. However, A11 should appear with either A13 and A14, which were already discarded as possible rules. Hence, the hidden rule being A04 can be inferred. **S4** has the option to write down a new system that can be used to confirm the correct inference of the hidden rule (and possibly gain a Laplace coin if needed), but since they have already earned it during **S3**'s turn, they spend that coin anyway to make the official guess: *A system must have the same number of input and output variables*, thus winning the game.

5. EXPERIENCES

During Spring 2022, two gaming sessions were organized. In the first session, the students were distributed among different tables, and the game was played independently at each table, using the *Classification of Systems* deck shown in Fig. 1. In the second session, which made use of the *Transfer functions* deck shown in Fig. 2, the students were distributed into two-players teams, and all the teams competed against each other (each team being a *Disciple of the Sacred Loop*) supervised by the lecturer (who participated to the game as the *Master of the Sacred Loop*).

It was observed that the first play mode presented some issues due to the composition of the tables. Some tables would be composed of highly performing students, who were able to understand quickly the game and thus engage into very competitive gameplay. Other tables were composed of students with mixed performances, and they would end up being dominated by highly performing students. Finally, tables with low performing students required hints and suggestions by the lecturer in order to advance further with the game and get closer to discovery of the hidden rule. The quantitative data reported in the next Section shows that the impact these issues had on the students' experience was all in all limited. However, it is worth mentioning that the above issues were all reduced in the team-based mode, which actually featured an increased communication about the content of the subject, between the players of the same team. Based on these observations, we would recommend playing the game with teams of two or three players, possibly accounting for well-discussed group formation strategies reported in the literature about *cooperative learning* [van der Laan Smith and Spindle, 2007].

5.1 Analysis of the quantitative data

This section describes and explores the perspectives of the participating students while experiencing the Control Zendo boardgame. The quantitative data was collected utilizing a questionnaire survey. A total of five areas, or constructs, concerning learning through this game were investigated. The items were rated based on the Likert's scale of 5 ordinal measures. The questionnaire was sent to all of the students who participated to the organized gaming activities, with a total of 16 responses returned. The quantitative data is summarized in Table 2.

Affective factors (Items 1, 6, 14 and 15) The participants reported their learning experience of playing Control Zendo to be fun (M=4.8125), motivational (M=4.37), inspiring (M=4.35) and confidence-boosting (M=4.06). Apart from the fun factor, while many students may be afraid of making mistakes

Participating in the boardgame has...	Do not know (N/A)	Strongly disagree (1)	Disagree (2)	Neutral (3)	Agree (4)	Strongly agree (5)	**Mean**
1. motivated me to learn	0	0	0	0	10	6	**4.3750**
2. helped me learn in a creative way	0	0	0	1	6	9	**4.5000**
3. increased my awareness in the topic I was learning	0	0	0	2	6	8	**4.3750**
4. helped me think more critically	1	0	0	3	6	6	**4.2000**
5. encouraged me to collaborate more with my peers	0	0	0	3	8	5	**4.1250**
6. boosted my confidence in learning the topic	0	0	1	2	8	5	**4.0625**
7. allowed me to discover the knowledge I needed to learn	0	0	0	2	8	6	**4.2500**
8. helped me observe my peers while playing the game	1	0	1	3	8	3	**3.8667**
9. helped me develop relevant skills	0	0	0	4	5	7	**4.1875**
10. facilitated my deeper understanding of the topic	0	0	1	0	10	5	**4.1875**
11. encouraged me to develop problem solving skills	0	0	1	2	6	7	**4.1875**
12. helped me communicate with my peers more	1	0	0	3	8	4	**4.0667**
13. helped me focus on learning	0	0	0	2	11	3	**4.0625**
14. inspired me to play more such games in my courses	0	0	0	1	8	7	**4.3750**
15. been a fun experience	0	0	0	0	3	13	**4.8125**
16. generated meaning towards my study	0	0	1	3	6	6	**4.0625**
17. helped with my thinking process	0	0	0	2	9	5	**4.1875**

Table 2. Quantitative data about the students' experience with the Control Zendo boardgame.

in traditional classroom learning, most did not mind making mistakes while playing a game. Competition, through trial and error brings accomplishment of figuring out the hidden rule.

Collaborative learning (Items 5, 8 and 12) The participants stated that Control Zendo offers opportunities to collaborate with peers in learning (M=4.12). In playing games, players acquire social skills of communicating more with their peers (M=4.06). It also trains players to observe their peers (M=3.86), wait for turns, plan while waiting, and accept their loss as well as enjoy their victory.

Higher-order thinking (Items 4, 11, 17) The use of Control Zendo could enhance the participants' thinking skills (M=4.18). The game involved them to think about rules actively. It can be used to develop higher-order thinking skills among students. They reported that it helped them to think about the subject more critically ((M=4.20), and allowed them to exercise problem-solving skills (M=4.18).

Metacognition (Items 2, 3, 7, 9 and 13) They are the learning processes the participants mentioned they used to plan, monitor, and assess their understanding and performance while playing the game. The Control Zendo was designed to integrate learning with game play, so that the learning goal of finding out the hidden rule is integral to the game, and the game is an integral part of the learning process.

Playing the Control Game helped them to be creative in their learning (M=4.5), increased their awareness in the topic they were learning (M=4.37), allowed them to discover the knowledge they needed to learn (M=4.25). They thought playing the Control helped them develop relevant skills (M=4.18) and focus on their learning (M=4.06).

Projected future use (Item 16) The participants found that it generated meaning towards the topic they were studying (M=4.06) as the game-based learning promised benefits in their learning in the future.

6. CONCLUSIONS

This paper presented the Control Zendo game, which has been used successfully in the course ELE320 - Control Systems at the University of Stavanger. The game is an adaptation of the popular game Zendo, and it involves applying inductive logic to discover a hidden rule which is related to theoretical control content taught in the course.

The paper has described the rules of the game, has shown an example of gameplay, and has discussed the experiences with the game during Spring 2022, supported by quantitative data collected utilizing a questionnaire survey. Overall, the sixteen participants were satisfied and found the Control Zendo effective for learning. The numbers from the survey were considerable evidence that these engineering students could learn through this inductive logic game. In particular, the game had a positive impact on different areas related to learning, such as affective factors, collaborative learning, higher-order thinking, metacognition, and projected future use.

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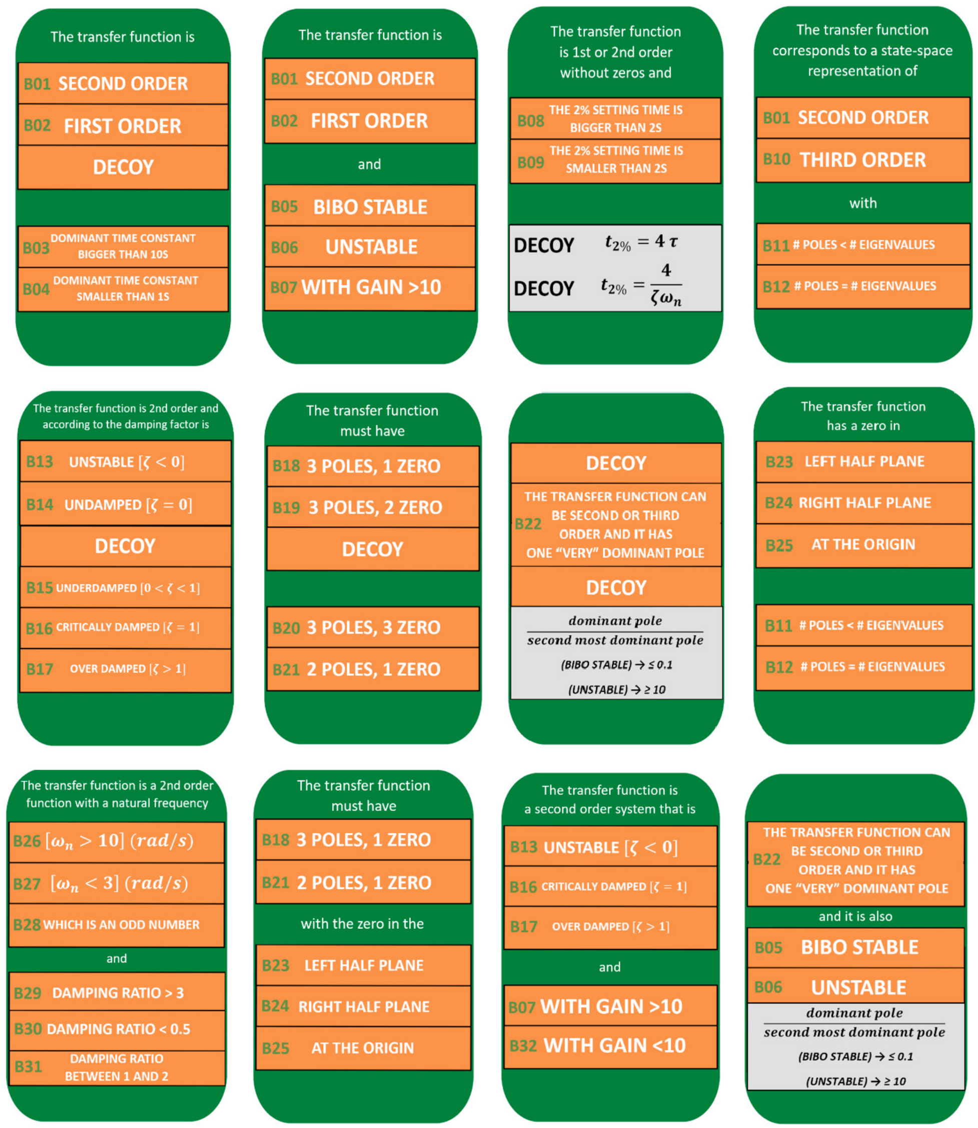

Fig. 2. *Transfer functions* deck.

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