An Innovative Project of a Bionic Robot for Social Applications in Felinotherapy

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Abstract: The paper describes an innovative design of a bionic robot for applications in felinotherapy supporting hospital and home psychotherapeutic treatment of bedridden children and adults. The project was engineered by biomimicrating a biological cat, reaching its robotic model. Particular attention in this process was devoted to capturing the essence of feline motorics behavior and the possibility of mapping them in a mechatronic model. The geometry, kinematics and kinetics of this model were analyzed, creating assumptions for its practical implementation in the real mechanism of cat skeleton movement. The used software used the topology of elements in *Autodesk Fusion 360 Simulation* workspace by performing the critical elements of the mechatronic model in print using SLS technology. The work was also supported by a graphical simulation in the *PyBullet* environment.

Keywords: robotics, bionics, biomimicry, felinotherapy, robotic cat, 3D modeling, movement mechanism, geometry, kinematics, kinetics, motor drives

1. Introduction

Felinotherapy – interchangeably, in relation to cats' therapy, a term used is a combination of two words from two languages: Latin *felis* – cat and actually *felino* – as an adjective and Greek *θεραπεία*, *therapeia* – care, treatment [1]. One of the methods of using animals in psychological treatment, called in English *pettherapy, animaltherapy* or also colloquially *zootherapy*. These methods were initiated and developed by Boris Levinson, an American child psychiatrist, in the years 1958–1964 [5].

The cat, as a therapeutic element in the field of *pettherapy*, was introduced by the Brazilian doctor Nise de Silva already in the middle of the last century. She stated [21] that contact with a cat improves our mental and physical condition, even just observing its behavior and being in its company helps to reduce the feeling of loneliness, depression and stress, increase mobilization to act and undertake various forms of activity promoting mental health. Not to mention the analytically determined stimulation of the human body to secrete endorphins, lowering blood pressure, the level of triacyglycerol and even cholesterol. Also simulate the immune system to function [23, 24].

Fig. 1. Half-blood of *Maine Coon*, one of the authors of the article – the geometric dimensions of this cat and its motor behavior were used to develop the assumptions and concept of the construction of the mechatronic model of the mechanism of cat movements
Rys. 1. Półkrwi *Maine Coon* jednej z autorek artykułu – rozległości geometryczne tego kota oraz jego zachowania motoryczne posłużyły do opracowania założeń i koncepcji konstrukcji mechatronicznego modelu mechanizmu kocich ruchów

A significant problem in *felinotherapy* is the choice of cat breed. Of the many cat breeds, the *Maine Coon* breed is especially predestined here. They are very large cats, up to 40 inches long, larger than all the others, but very affectionate and sociable, interesting people, especially gentle with children. Due to their friendly personality, these beautiful cats are usually referred to as gentle giants (Fig. 1) [22].

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Two types of therapeutic programs applying *felinotherapy* are becoming popular nowadays [5, 23, 24]:

- therapy for children with mental disorders – used in cases of autism, ADHD, mental retardation, mental illness, Asperger's syndrome and various emotional disorders such as shyness, fear of speaking and lack of self-confidence,
- therapy for the elderly, especially those suffering from depression and under stress. A cat is proposed as a companion in the life of an elderly, lonely, disabled person, motivating him to be active in the form of caring for him, reducing the feeling of loneliness. During direct contact with the cat (lifting, stroking and cuddling) the human muscles heat up (the cat's body temperature is 38–39 °C), which improves blood circulation and removes the feeling of cold in the feet and hands, relieves rheumatic pains, with phlebitis. Cats instinctively look for sore spots on the human body and lay down on them, warming up these places. They have a general soothing effect on mood swings and have a relaxing effect on the human psyche.

However, *felinotherapy* cannot be used by people allergic to cat hair, suffering from ailurophobia, i.e. irrational, beyond reasonable fear of cats and people aggressive towards animals, including cats. Also people who require care for their immunity, e.g. in the case of infectious diseases and the use of chemotherapy. The problem is, of course, the consent of a seriously ill person's physician or caregiver to the presence of a live animal in a room, in an intensive medical or inpatient hospital ward, requiring sterilization, decontamination, disinfection, and generally strict antisepsis of the environment. The more so that cats also require systematic care, which can, for understandable reasons, be undertaken only by selected treatment facilities, primarily care facilities, e.g. orphanages and autumn-life homes.

These problems prompted the authors to address the problem of building a mechatronic cat model that could replace a living soft toy and play the role of a companion for children and adults in a hospital, hospitalization or home environment, characterized by the durability and functionality of robots used today in the manufacturing industry [13, 15].

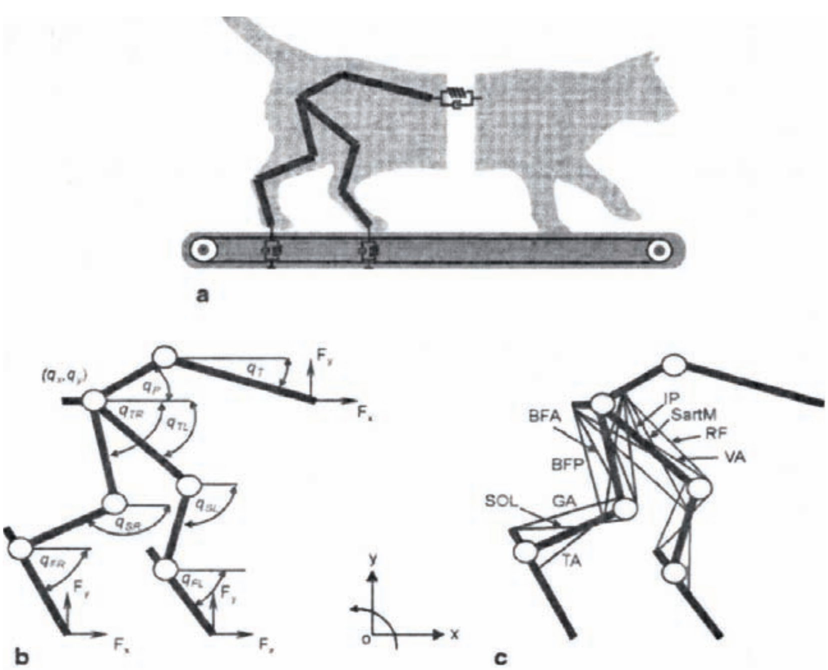


Fig. 2. Representation of the muscle and skeletal model of the cat's hind limbs: a) the principle of studying the cat's gait using motion capture cameras cooperating with sensors placed on the animal moving on a treadmill [27], b) defined angles of movement of the skeleton segments of the cat's hind limbs, c) simplification of the view of the muscles the cat's hind limbs defined in the coordinate system placed in the middle of the drawing [28]

Rys. 2. Reprezentacja modelu mięśniowo-szkieletowego tylnych kończyn kota: a) zasada badania chodu kota z zastosowaniem kamer motion capture współpracujących z sensorami umieszczonymi na zwierzęciu poruszającym się na bieżni [27], b) zdefiniowane kąty ruchu członów szkieletu tylnych kończyn kota, c) uproszczony zarys widoku mięśni tylnych kończyn kota, zdefiniowany w układzie współrzędnym umieszczonym pośrodku rysunku [28]

2. The challenges of the bionic cat project

The first and main challenge of the described project is the cat itself. With its skeletal flexibility and the agility of the muscles of the body, and with all its wealth of possibilities for movement. Starting with cats' favorite, frequent falling asleep in the form of a rolled up ball, by immediately waking up from sleep under the influence of a possible or existing threat, walking, and usually running, with the phases of contact (stance) and phases of no contact (swing) of the paws with the ground, with excellent climbing skills, even tall trees, to overcome all obstacles. And falling, even from great heights, always on the (proverbial) four paws. And jumps, without a run-up, even 6 times the distance of its own length. And gentle, unprecedented in comparison to other domestic animals, patting each other with its two front paws, with a pleasant purr and looking into the eyes of the person with whom the cat wants to spend a few moments, e.g. a little nap ... and an observer of the behavior of these lovely animals ...

There are works in the field of veterinary medicine that relate to the mechanics of cat movement. The simplest method of its examination is the use of the motion capture system, consisting of cameras cooperating with sensors placed on the animal's skin [31]. Cats are encouraged, usually with a tasty reward, to walk (run) a designated section of road or walk on a treadmill (Fig. 2a). On the basis of the collected data, the changes in the position of these points in time are created for different motor behaviors (Fig. 2b, c)

An important place in the project was taken by the aforementioned *Maine*

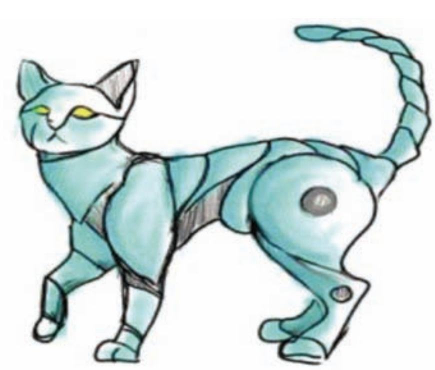


Fig. 3. The first sketch of the *Cthulhu2.0* bionic robot model in the project [8]

Rys. 3. Pierwszy szkic modelu bionicznego robokota *Cthulhu2.0* w projekcie [8]

Coon half-blood (Fig. 1) by one of the authors, serving as a reference model and a source of initially fantastic design inspirations (Fig. 3). The cat's name is *Cthulhu* (called *"ktulu"* ...) – it was inspired by a fictional creature from the fantasy novels of the American writer Howard Philips Lovecraft (1890–1937). Hence the name of the robot from the described project as the second such fantastic creature, i.e. *Cthulhu2.0*.

The second challenge of the project was the rapidly growing market of bionic products [3, 6, 11, 19] that is solutions shaped by a form found in nature, but embedded in the area of influence of various practical and functional requirements related to mechatronic technology [9, 10]. The first, innovative and technically advanced presentation of bionic solutions related to the developments of Festo AG & KG took place in 1913 at the Warsaw University of Technology [4, 14].

The boundaries of the aforementioned bionic products market are, on the one hand, interactive toys for children, and, on the other hand, robotic solutions with dominant bionic characteristics, with industrial applications already proposed or anticipated in the near future [16, 17].

An example of a solution from the first group is an interactive, plush robotic catcher (Fig. 4), which moves and meows when you press its back or clap its hands. Then one of the 6 sequences of moving the front and hind legs and meowing is activated randomly, unfortunately very far from what we call a cat meowing or purring.

The second group includes mainly cobots, i.e. cooperative robots, adapted to direct cooperation with humans (Fig. 5a) and mobile, walking robots (Fig. 5b).

A good example of a collaborative robot is *BionicCobot*, developed at Festo AG & KG [13, 15]. The solution was known already in 2017, but still respects the enormity of the problems that have been successfully solved. The robot's mechanism and its geometric extensions perfectly meet the ergonomic requirements of the human figure, as well as its speed, acceleration and load parameters. Its movements can be programmed in all three ways used in conventional, on- and off-line robotics, and it is particularly convenient to program by teaching that meets the requirements of collaboration by guiding the mechanism by hand. This was achieved by the consistent use of a pneumotronic servo drive with vane rotary actuators. Thanks to this, the mechanism is "soft", it is smoothly guided by hand, programming of the position and path of movement is therefore very easy, even in conventional settings of the mechanism that cannot be achieved by robots, e.g. ball, cat, curl (Fig. 5a).

An equally interesting product of this group is *OpenDog*, a walking robot, an example of the Do It Yourself (DIY) solution, which is becoming more and more popular in the group of people who undertake their own "home" work. In this category, one can more and more often meet bionic robots, imitating various animals, even quadrupeds, but with quite limited movement mechanisms (Fig. 5b).

The aforementioned necessity to install the *Cthulhu2.0* bionic robot in the area of practical requirements related to *felinotherapy* was another challenge of the described project. Used here are both available publication sources, e.g. Fig. 6 [27–29] and Tab. 1 [30], and above all, own observations of the behavior and activities performed by living *Cthulhu* (Fig. 1). Each of these activities was then segmented into individual positions analogous to the film frames. On this basis, it was possible to determine the ranges of motion of the *Cthulhu2.0* model. The following activities were considered important:

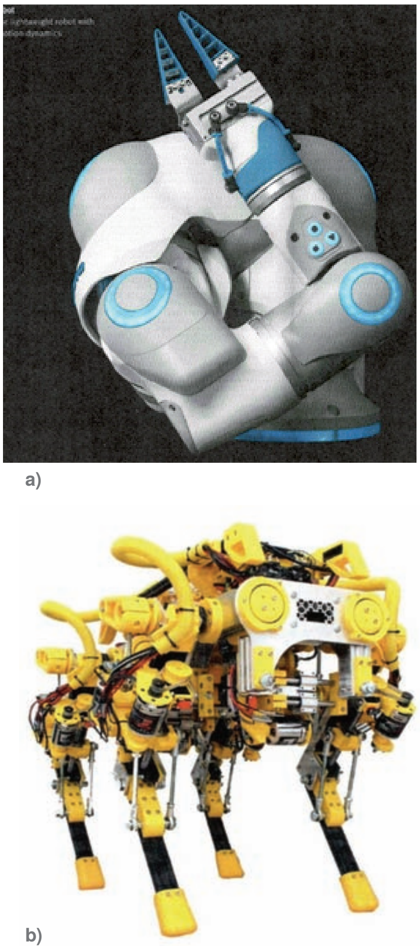


Fig. 5. Contemporary bionic robots: a) industrial cobot *BionicCobot* of Festo AG & KG with pneumotronic vane servo motors enabling the bionic twisting-arranging of the kinematic chain of the mechanism [13, 15], b) the *OpenDog* mobile walking robot, designed for your own amateur 3D printing using components from hobby stores (James Burton) [25]

Rys. 5. Współczesne roboty bioniczne: a) kobot przemysłowy *BionicCobot* holdingu Festo AG & KG z pneumotronicznymi serwosiłownikami łopatkowymi umożliwiającymi przedstawione na zdjęciu bioniczne skręcone-ułożenie łańcucha kinematycznego mechanizmu [13, 15], b) robot mobilny kroczący *OpenDo*g, przeznaczony do własnego, amatorskiego wykonania drukiem 3D z wykorzystaniem komponentów ze sklepów dla hobbystów (James Burton) [25]

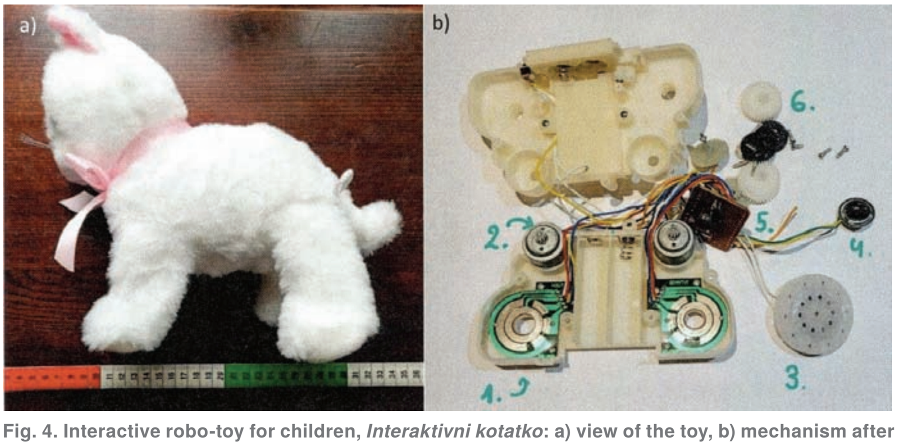


Fig. 4. Interactive robo-toy for children, *Interaktivni kotatko*: a) view of the toy, b) mechanism after disassembly into its components: 1 – drive position sensors, 2 – two electric drive motors, 3 – loudspeaker, 4 – touch sensor, 5 – controller board, 6 – transmission (Fenghua Fun Toys)

Rys. 4. Robo-zabawka interaktywna dla dzieci, *Interaktivni kotatk*o: a) widok zabawki, b) mechanizm po rozebraniu na części składowe: 1 – sensory pozycji napędu, 2 – dwa elektryczne silniki napędowe, 3 – głośnik, 4 – sensor dotyku, 5 – płytka sterownika, 6 – przekładnie napędowe (Fenghua Fun Toys)

- *Starting Position* – a natural position from which it is possible to perform any activity, in this position the cat stands still on all four paws,
- *Walk* 1 – this is how the slow movement of the cat in the space of the home environment was called (jog),
- *Walk* 2 – faster jog observed when calling "*Cthulhu*" or the cat's increased interest in elements of the environment,
- *Jump* – a sequence of movement consisting of three phases, preparation for jump, lift-off and landing phases, the jump is made from the lower landing surface to the higher surface target surface,
- *Jump Down* – an action similar to *Jump*, it is also a sequence of three phases, but the starting surface is higher than the target surface,
- *Sit* – the cat moves to a sitting position and remains in a sitting position,
- *Leaving the Sit* – leaving the sitting position to the *Starting Position,*
- *Lying Down* – the cat moves to this position from the *Sit* down position and remains in this position; Due to the limited load capacity of *Cthulhu2.0* and its weight (approx. 8 kg), it was decided not to take into account the scenario of going directly from the *Starting Position* to the *Lying* activity. The cat's paws are folded under his body, the tail is curled around,
- *Exit from Lying Down* – leaving the *Lying Down* position to the *Start Position.*

In addition, each of these activities is to be varied with the tilt of the head or the selected shape of the tail, which will give *Cthulhu2.0*'s behavior even more realism.

Based on the collected publication data [7, 32] and own research [8], a model of the robot's skeleton was created from segments connected by joints with one degree of mobility. The simplified implementation becomes easy to implement, both in simulations and in the later stages of prototyping the *Cthulhu2.0* robot mechanism.

This process was carried out using the anatomical model of the cat's skeleton (Fig. 7a), mapping the geometric extensions of the skeleton segments. Then, the preliminary arrangement of the junction points (*JP*) where the motion will take place was made. Each segment was approximated in *Autodesk Fusion 360 Simulation* by a solid that corresponds to the volume of the cat's dimensions. In this way, a model was created consisting of basic solids connected with each other by means of joints-junction points with a defined mobility value (Fig. 7b).

The limbs and parts of the body are shown by chains of solid cylinders. The tail was also brought closer with the help of solids, but cuboids. On the basis of such a simplification, it was possible to initially estimate the dimensions and masses of the segments needed to start calculating the kinematics and kinetics of the robot's mechanism. The masses were estimated by defining the material from which the element will be made with the use of *AF*360 *Simulation.* At this stage, it was already assumed that the mechanism would be made in 3*D* printing technology, so it was assumed that the segments would be made of resin with different values of mechanical strength.

In order to compare the effects that can be achieved with computer graphics programs with engineering programs such as *AF*360 *Simulation*, a simulation-animation of the robot's skeleton motion was run in the *Blender* environment, using the developed skeleton model. *Blender* introduces "bones" that animate the movement of the robot's skeleton. An already developed model was not used because the *Blender* environment was found to allow for better animations of the anatomical structure.

With the help of the script, the model created in *AF360 Simulation* was imported into the *PyBullet* environment. This program has the potential to transform animated motion into robot movements using the *Robot Operating System* (*ROS*) platform. It also supports the kinematic and kinetic analysis of the model

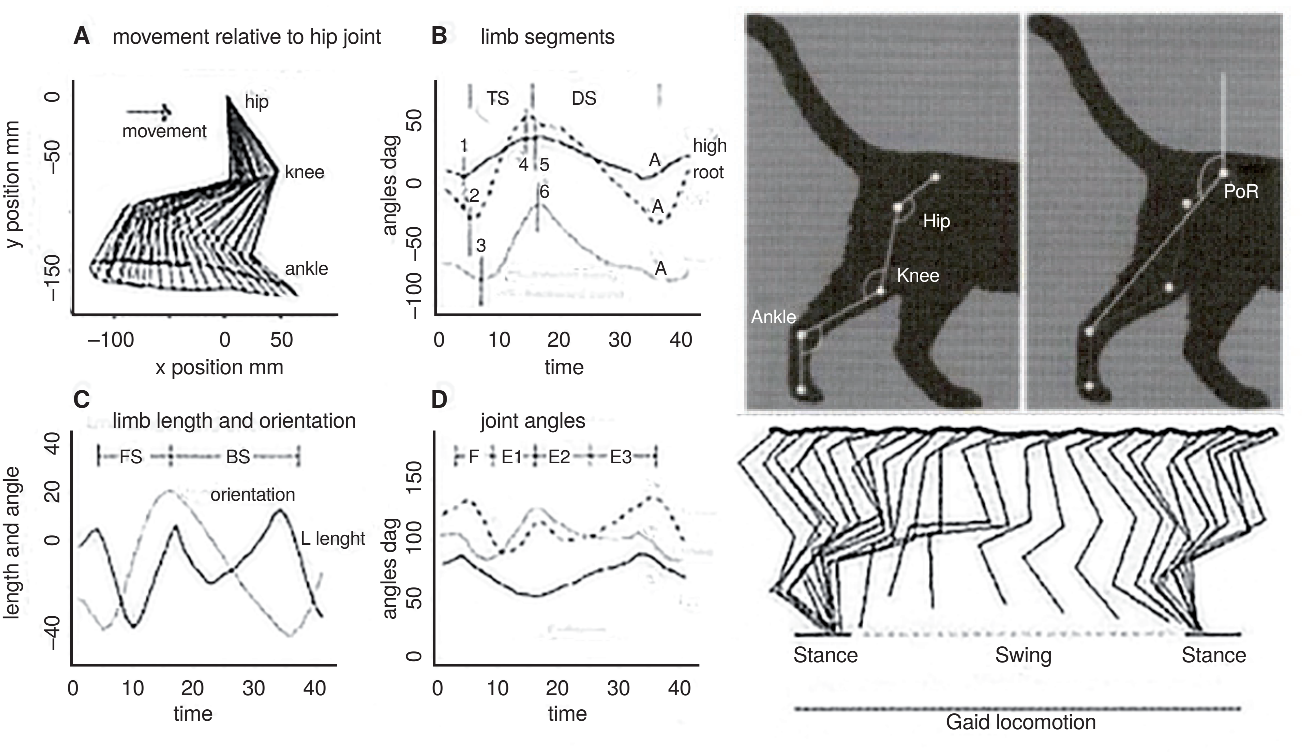


Fig. 6. Traffic analysis charts of a cat during a walk: A) movement relative to the hip joint, B) change the angle value between the limb segments, C) changing the length and position of the limb, D) changing the angles in the individual joints – on the right drawing: show motion simulation rear limb cat, contact phases of paws with the ground (stance) and the phases of lack of contact of paws with a substrate (swing) [27, 29]

Rys. 6. Wykresy analizy ruchu tylnej kończyny kota podczas chodu: A) ruch względem stawu biodrowego, B) zmiana wartości kąta pomiędzy członami kończyny, C) zmiana długości i położenia kończyny, D) zmiana wartości kątów w poszczególnych stawach kończyny – po prawej rysunku: przedstawienie symulacji ruchu tylnej kończyny kota, fazy kontaktu łapy z podłożem (stance) i fazy braku kontaktu łapy z podłożem (swing) [27, 29]

Tab. 1. Movement ranges of domestic cat joints according to [30]
Tab. 1. Zakresy ruchu stawów kota domowego wg [30]

		Angle measurement for ROM											
		Mean = SD (°)			95% CI of the mean (°)			CV (%)			Median (°)		
Joint	Position	Non	Sed	Rad	Non	Sed	Rad	Non	Sed	Rad	Non	Sed	Rad
Carpal	Flex	22 = 2	22 = 1	21 = 3	22–23	21–22	19–22	7	6	13	22	22	20
	Ext	198 = 6	198 = 5	197 = 5	196–199	197–199	195–199	3	2	2	198	193	197
	Val	10 = 2	11 = 2	11 = 1	9–10	10–11	11–12	23	19	12	10	10	11
	Var	7 = 2	7 = 2	7 = 1	6–7	6–7	6–8	25	30	20	7	6	7
Elbow	Flex	22 = 2	22 = 1	23 = 2	22–23	22–22	22–24	8	6	9	22	22	23
	Ext	163 = 4	165 = 3	167 = 3	162–164	164–165	166–169	3	2	2	162	164	168
Shoulder	Flex	32 = 3	32 = 2	36 = 6	31–32	31–32	34–39	8	8	16	32	32	36
	Ext	163 = 6	167 = 3	162 = 4	162–165	167–168	160–163	4	2	2	164	168	163
Tarsal	Flex	21 = 1	22 = 1	19 = 1	21–22	21–22	19–20	7	5	7	22	22	19
	Ext	167 = 4	168 = 2	169 = 4	166–168	167–170	167–170	3	1	2	167	168	170
	Val	7 = 2	7 = 2	9 = 3	7–8	7–8	8–11	32	22	32	7	7	8
	Var	10 = 3	11 = 3	12 = 2	10–11	11–12	11–13	26	23	19	10	11	12
Stifle	Flex	24 = 2	24 = 3	21 = 2	24–25	24–25	20–22	9	13	11	24	24	21
	Ext	164 = 4	164 = 3	159 = 9	163–165	164–165	155–163	2	2	6	166	164	162
Hip	Flex	33 = 3	33 = 2	36 = 4	32–33	32–33	34–38	9	7	11	32	33	36
	Ext	164 = 4	166 = 4	163 = 4	163–165	165–167	161–164	2	2	3	164	166	164

CI = Confidence interval. CV = Coefficient of variation. Non = Nonsedated cats. Sed = Sedated cats. Rad = Radiographs. Flex = Flexion. Ext = Extension. Val = Valgus angulation. Var = Varus angulation.

mechanics and allows you to check the operation of the robot skeleton under force, moment and gravity loads in a virtual environment.

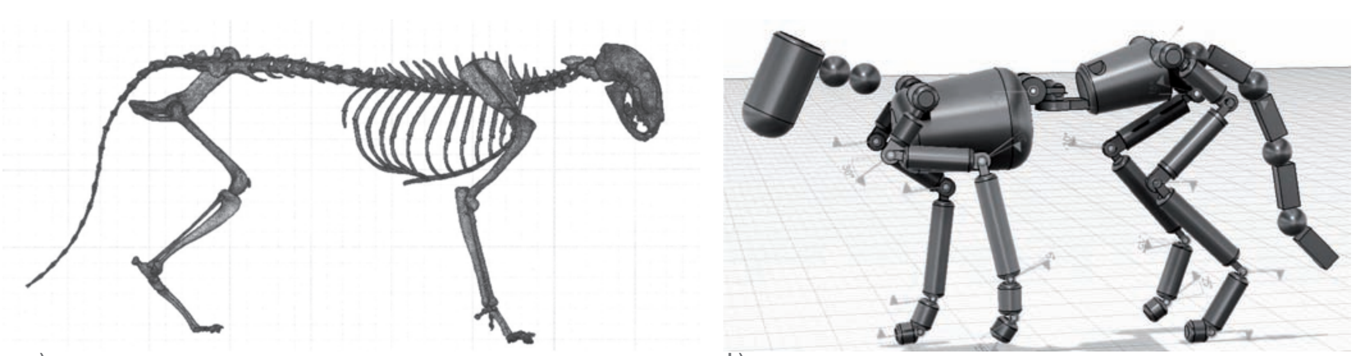
3. Assumptions of the bionic cat project

A safe, defined by the standards *Men-Robots-Collaboration* (*MRC*) [13], functional cooperation of the *Cthulhu2.0* robot with people who passively and actively use *felinotherapy* was established – the following kinematic and load limitations were adopted:

- for the speed of rotational (angular) movements of the *paws* – the maximum value for the individual five parts of the cat's *paws*, the same for the front and hind legs, is 500°/s, 750°/s, 590°/s, 1.2°/s, 1.6°/s (from *shoulder-blade*, *shoulder*, *arm, forearm* to *wrist*). These are the maximum values that can also be safely achieved by *Cthulhu2.0* limbs,
- for the speed of linear movements of the cat's front and hind legs – resulting from the above-mentioned values of rotational movement and the geometric extent (length) of the *paw* segments – its maximum value for *Cthulhu2.0* limbs cannot exceed 1 m/s,
- for the mass of the mechanism – the value of the mass of the *Cthulhu2.0* mechanism was assumed to be close to the mass of the cat, here the assumption was a comparable size – geometrical extent of the robot and the size of the reference *Maine Coon* cat (Fig. 1),
- for the mass load of the mechanism – it was assumed that the maximum external mass load of each *Cthulhu2.0* limb may not exceed 1 kg.

Another, already constructive, assumption of the *Cthulhu2.0* project, as an imitation of a cat, was to adopt the following conditions for the construction of its mechanism:

- two front and two hind limbs of *Cthulhu2.0* are treated as mirror images,
- these limbs, imitating the anatomical structure of the cat's skeleton (Fig. 7a), are kinematically composed of a chain of two groups of segments $\{C_R, B_{R1}, B_{R2}, B_{R3}, B_{L1}\}$ for the above-mentioned *shoulder-blade*, *shoulder*, *arm*, *forearm* and *wrist*, and the segment *feet* $\{B_{L2}\}$. This structure provides 5 degrees of limb mobility, treating the cat's foot member as a robot tool (Fig. 7b),
- at the point of connection of segments (*joints* in a cat), tension mechanisms are to be used (Fig. 8), which allows to avoid the so-called offsets of electric drive motors, distorting the imitation of anatomical joints and allowing the most faithful representation of the cat's anatomy in the model. The transmission of the drive through the tendons also allows the motors to be placed close to the model body [20]. It is important because the work of the mechanism depends to a large extent on the weight distribution, the lower mass of the limbs means their lower inertia and better dynamics of movement,
- it was assumed that the gears were not used in the drives of the C_R and B_{R1} segments (the cat's *shoulder-blade* and *shoulder*), which ensures a reduction in the volume of the structure in this part of the *Cthulhu2.0* mechanism – it was inspired by the construction of a walking robot designed by MIT Biomechanics Robotics Lab. Resig-



a) b)

Fig. 7. The stage of simplifying the cat's skeleton for the development of a bionic model: a) anatomical model of the domestic cat skeleton [26], b) visualization of the simplified kinematic scheme of the *Cthulhu2.0* robot mechanism developed in the *Autodesk Fusion 360 Simulation* environment: 22 ponds joints-points of connection (*JP*) are marked with a flag, segments of the mechanism made of solid basic – cylinders and cuboids

Rys. 7. Etap uproszczenia szkieletu kota dla opracowania modelu bionicznego: a) anatomiczny model szkieletu kota domowego [26], b) wizualizacja uproszczonego schematu kinematycznego mechanizmu robokota *Cthulhu2.0* opracowana w środowisku *Autodesk Fusion 360 Simulation*: 22 stawy-punkty złączenia (*JP*) oznakowano flagą, człony mechanizmu wykonano z brył podstawowych – walców i prostopadłościanów

Fig. 8. Linkage mechanism for *Cthulhu2.0* [20] – external view
Rys. 8. Mechanizm cięgnowy [20] połączeń mechanizmu *Cthulhu2.0* – widok od zewnątrz

nation from the toothed belt transmission also reduces the failure rate of this structure,
- it was assumed that the drive motors were placed as the heaviest components of the mechanism, as close to the robot's mass center as possible – it improves the stability of the movement of the entire mechanism,
- flexible, even if it is implemented to a limited extent, the construction of the spine and tail of the *Cthulhu2.0* mechanism was also adopted – this has a positive effect on the speed and naturalness of gait achieved by walking robots – this was confirmed by the study of the motor activity of *quadrupeds* with a *cheetah-like* structure. The tail also acts as a counterweight to the robot's head, in which it is planned to place electronics that load it by gravity,
- the center of mass of the mechanism was planned to be placed in the geometrical center of the structure. This adoption allows the weight of the robot to be evenly distributed among the four limbs, relieving the drives and preventing them from overheating.

4. Selected fragments of the description of the construction and implementation of the bionic cat project

The elements of the *Cthulhu2.0* model developed in the project (Fig. 9) were made thanks to the courtesy of the Festo Polska Application Center, which provided technically advanced *Formlabs form 2* printers. For *3D* printing in the *SLA technology*, a liquid, laser-hardened photopolymer resin was used. Standard *Draft* resin non-load bearing elements, e.g., anti-damage guards, are light colored in Fig. 9, and weighted components are made of *Clear* resin for smooth, accurate and high-strength printing – dark colored. This material is used for making joints and more important joints of the mechanism.

The predominance of light color in Fig. 9 is due to the desire to present cable mechanisms ensuring movement in the connections of the segments of the robot mechanism.

Before printing, all elements were optimized in the *PreForm* software dedicated to *Form* 2 printers (Fig. 10). The largest printable dimension was 17.5 cm. This means that it was necessary to split some parts of the model and design them in two parts printed separately.

The weight of the robot model has a decisive influence on the engine load, and thus on the dynamics of the mechanism. The easiest way to reduce its value was to remove unnecessary material from its constituent elements. This goal was achieved by two methods. The first was "manual optimization" when designing the mechanism, the second was the method of using the simulation tool and automatic shape optimization available

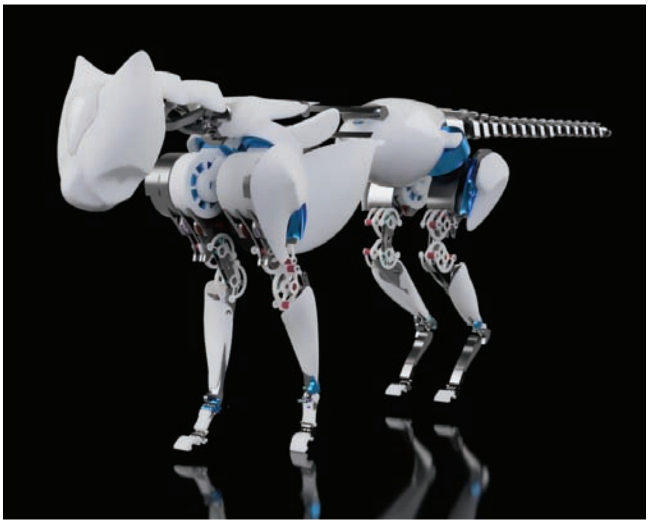


Fig 9. The final model of the bionic *Cthulhu2.0* robot in the project [8], visualization made in *Autodesk Fusion 360 Simulation*, view from the left side in profile – visible movement joints of the joints-segments, made as tension mechanisms. The light color marks the casing segments of the mechanism made of *Draft* resin, the dark color – operating under load, made of *Clear* resin
Rys. 9. Finalny model bionicznego robokota *Cthulhu2.0* w projekcie [8], wizualizacja wykonana w *Autodesk Fusion 360 Simulation*, widok ze strony lewej z profilu – widoczne połączenia ruchowe członów – *stawy*, wykonane jako mechnizmy cięgnowe. Kolorem jasnym oznaczono człony osłonowe mechanizmu wykonane z żywicy *Draft*, kolorem ciemnym – działające pod obciążeniem, wykonane z żywicy *Clear*

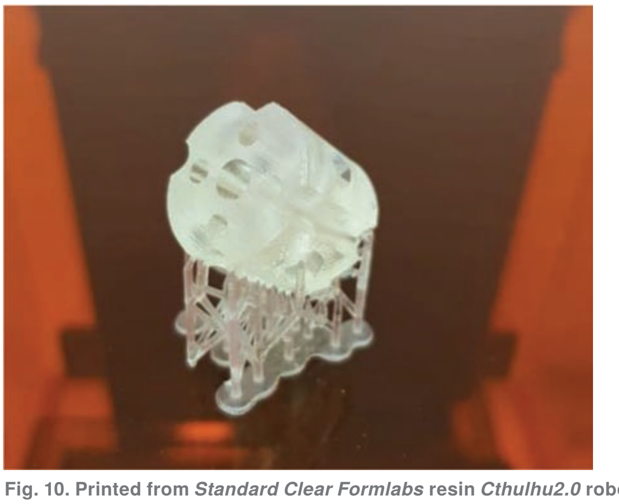


Fig. 10. Printed from *Standard Clear Formlabs* resin *Cthulhu2.0* robot "*tail*" segment
Rys. 10. Wydrukowany z żywicy *Standard Clear Formlabs* człon „*ogona*" robokota *Cthulhu2.0*

in *AF 360 Simulation*. Based on the original shape and input parameters in the form of loads, the simulation calculates how much material can be removed without affecting the mechanical strength of the element.

It was assumed that the center of mass and also the geometric center of the robot, similarly to the anatomical cat, is located in the *chest*, behind the line of the front *paws*. This feature will allow the cat's weight to be evenly distributed between the four *paws* and four limbs of the robot, relieving the drive motors and preventing them from overheating.

It was also assumed that the trajectory of movement of each limb of *Cthulhu2.0* is determined by the *Tool Center Point* (*TCP*), suspended at the end of the B_{L1} segment, at the junction with the B_{L2} (*foot*) segment. This location was chosen because the cat, while walking, in this place (point) exerts the greatest pressure on the ground.

The C_R segment (equivalent to a cat's *shoulder-blade*) is responsible for the adduction and abduction movement of a limb (cat's *paw*). Its main element is an engine with a cover. This segment is attached directly to the body. Similar to the cat's *scapula* it is angled from the vertical axis. The consequence of such a construction is also an inclined trajectory, along which the limb is abducted. This action is intentional as it makes the movement more "anatomical". The segment can deflect the *shoulder-blade* limb *Cthulhu2.0* upwards from the starting position up to an angle of 80° with respect to the robot body and 30° inwards under the robotic cat body.

The B_{R1} segment is placed on the preceding C_R segment without the use of a reduction gear (ratio 1:1), directly on the axis passing through the center of the drive motor. It is the equivalent of a cat's *shoulder*, it is responsible for the forward and backward movement in relation to the robot's body. Together with the C_R element, it forms a substitute for the "ball joint" and completes the range of motion of the cat's anatomical structure. Its structure is similar to the C_R segment. Its main components are the engine and its cover. The axis passing through the center of this segment coincides with the axis of the *shoulder-blade* joint. The range of motion is 100 degrees forward and 80 degrees backward, respectively, relative to the robot body, referring to the vertical axis of the base system.

The B_{R2} segment (equivalent to a cat's *arm*) is connected to the B_{R1} segment (equivalent to a cat's *shoulder*) also without using a reduction gear. However, it houses two of the three motors responsible for the operation of the cable mechanism (Fig. 11):

- a motor with greater energy efficiency drives the movement in the *elbow* joint through a 6 mm wide belt and toothed gear with a 3:1 gear ratio. The gear belt moves the spool to which the strands are attached. One end of the string is turned on the spool clockwise, the other end clockwise. The direction of the motor's movement is responsible for winding and unscrewing the bobbin. In this way, the tendons responsible for bending and extending the elbow connection are antagonistically tightened and loosened. This mechanism (Fig. 8) was developed on the basis of the solution proposed in the *LIMS*2 walking robot [18],
- a motor with lower energy efficiency, with an identical belt-toothed transmission, similarly drives the movement in a joint-joint connecting the B_{R3} segment (equivalent to a cat's *forearm*) with the B_{L1} segment (equivalent to a cat's *wrist*). The tendons with which it moves are threaded through the center of the *elbow* joint from the inside (Fig. 12a). Such a construction is possible thanks to the tangency of two circles forming the halves of the pond. These circles, moving in relation to each other, remain at a constant distance of $2r$ (r radius of the circle). Therefore, the tendons do not change their length and the movement of the "*elbow* joint" does not affect the movement of the joint following it.

The above-mentioned segments C_R, B_{R1}, B_{R2} and B_{R3} are, referring to the construction of industrial robots with a conventional chain structure, segments of the regional part positioning the robot effector in the working space. The consecutive parts of this structure are the local part, orienting the position of the effector [12, 13, 15]. In the case of *Cthulhu2.0*, these are two parts, the equivalents of the *wrist* and *foot* of the cat's *paw*, in the robot's mechanism marked as B_{L1} and B_{L2}.

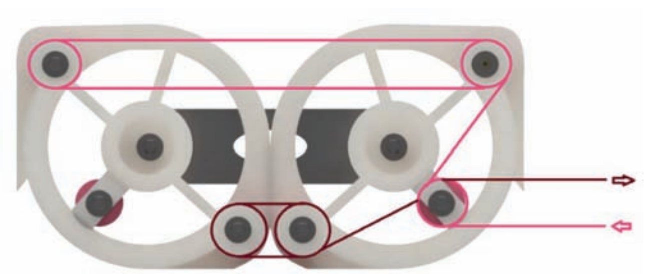
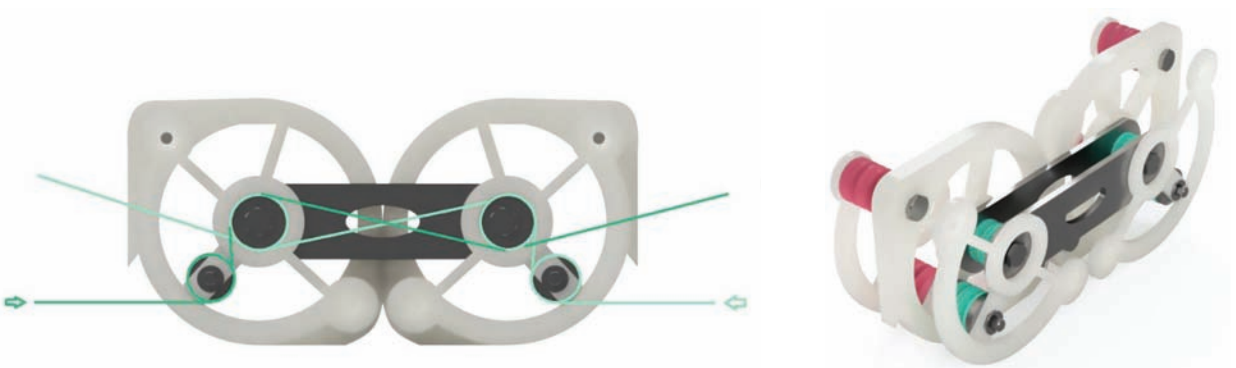


Fig. 11. Visualization of the "*elbow joint*" of the *Cthulhu2.0* limb: view of the routing of the tendons from the outside, the dark color marks the tendon currently wound on the shaft of the motor located in the preceding segment to the driven one – external view without tendons in Fig. 8

Rys. 11. Wizualizacja „*stawu łokciowego*" kończyny *Cthulhu2.0*: widok prowadzenia cięgien od strony zewnętrznej, ciemnym kolorem oznaczono cięgno aktualnie nawijane na wałek silnika położonego w członie poprzedzającym do napędzanego – widok od strony zewnętrznej, bez cięgien, Rys. 8

Fig. 13. View of the construction of the connection of the segments *BR*3 and *BL*1 of the *Cthulhu2.0*, the external elements (darker) allow the tendons to be pulled to the next joint-joint, the internal elements (lighter) allow the tendons to move this joint

Rys. 13. Widok konstrukcji połączenia członów *BR*3 i *BL*1 robokota *Cthulhu 2.0*, elementy zewnętrzne (ciemniejsze) umożliwiają przeciągnięcie cięgien do następnego połączenia-stawu, elementy wewnętrzne (jaśniejsze) umożliwiają cięgnom poruszanie tym połączeniem-stawem



a) b)

Fig. 12. Visualization of the *elbow* joint of the *Cthulhu2.0* limb: a) view of the routing of the tendons from the inside, the shown tendons do not affect the movement of the joint, they run to the next joint, b) view from the inside

Rys. 12. Wizualizacja stawu łokciowego kończyny *Cthulhu2.0*: a) widok prowadzenia cięgien od strony wewnętrznej, pokazane cięgna nie mają wpływu na ruch stawu, biegną one do stawu następnego, b) widok od strony wewnętrznej

These two segments, which form the local part of the robot, are an unusual solution and directly mimic the cat's anatomy. In the design of most existing *quadrupeds*, these segments are replaced with a flexible tip of oval shape, allowing movement on most surfaces. This simplifies the design and control of the motors, which works well when the main task of the robot is just walking. When designing the *Cthulhu2.0*, however, they wanted to give it orientation possibilities, enabling, for example, a lateral hitting of a ball with a *paw*, so these two additional elements were introduced.

The rods responsible for the movement of these two robotic cat segments are pulled through the B_{R3} segment. It also houses the motor driving the B_{L2} component (3:1 gear). It is connected with the local part by a joint structure with the principle of operation analogous to that of the *elbow* joint. However, this joint is much smaller, so in order to strengthen it, two interlocking coaxial toothed rollers have been added.

Fig. 14. Connection-joint of the local segments B_{L1} and B_{L2} of the *Cthulhu2.0* limb mechanism, driven by tendons drawn through the previous connection
Rys. 14. Połączenie-*staw członów lokalnych* B_{L1} i B_{L2} mechanizmu kończyny *Cthulhu2.0*, napędzany cięgnami przeciągniętymi przez poprzednie połączenie

B_{L1} is the only segment that differs in structure in the fore and hind limbs of *Cthulhu 2.0*. In the forelimb, it is shorter and allows the mechanism to slide and grasp objects a bit like the middle part of a human hand. As a hind limb, it is about three times longer and is used for stabilization, similar to the *foot*. It ends with a joint-joint, which is moved by the longest strands in the robot's mechanism.

The B_{L2} segment *kitty foot* (or *sole* ...), anatomically the cat's *toes*, has been treated in this design as a tool at the end of the kinematic chain of the *Cthulhu2.0* limb, imitating a cat's *paw* (Fig. 14). This made it possible to organize the calculations of kinematics and kinetics and to describe the kinematic structure of the kinematic chains of the robot's limbs, similar to the kinematic mechanism of an industrial robot. In the future, it will also allow to describe the so-called *approach vector*, that is, it will enable a strong orientation of this cat's *feet*. At the bottom of the *paw/foot* shown in Fig. 15, there is a recess in which a silicone cushion for cushioning the robot's gait will be placed (Fig. 15).

During its behavior, the cat's *tail* balances the remaining ones, i.e. the function of a counterweight. However, observing these behaviors of a living *Cthulhu*, one gets the impression that the *tail* is a separate "entity", moving independently of the rest of the cat body. When designing the *tail* for the *Cthulhu2.0* it was assumed with minimum requirements, it must have only two sections, each of which can bend completely independently. Each section requires the use of two motors and two pairs of cables responsible for its movement, e.g. the proverbial cat's tail bend. In total, therefore, 4 motors and 4 pairs of cables are required.

The *tail*, however, is mainly an aesthetic element of the *Cthulhu2.0* robot and does not carry loads. Therefore, it was planned to use low-power engines to drive it, selected so as not to increase the weight of the robot too much (Fig. 16).

The *body* of the robotic cat is the attachment point of the first segments of the four chain mechanisms of the *paw*-limbs, as well as the *tail* and *head* (Fig. 15). It is treated kinematically as the grounded "0" point of the coordinate system in which recursively kinematic and kinetic analyzes of the motor behavior of the listed components are carried out (Chapter 5). It has been designed so that it is possible to place the driving electrics and electronics controlling the model in it.

The "*chest*" and "*pelvis*" of the skeleton of are connected by a mechanism ensuring bending in two planes and rotation. Initially, it was planned to use a cable mechanism composed of three segments. This mechanism turned out to be not very stable, it

Fig. 16. *Cthulhu2.0* robot *tail*: visualization of the model ready for 3D printing
Rys. 16. *Ogon* robokota *Cthulhu2.0*: wizualizacja modelu gotowego do druku 3D

a) b)

Fig. 15. *"Cat's feet"* looking at them from the side (a) and partially at the rear (b), visible recess intended for a silicone cushion that cushions the robot's gait, also visible position of two connections-joints of local part segments B_{L1} and B_{L2}, Fig. 13 and 14
Rys. 15. „*Kocie łapki*" patrząc na nie z boku (a) i częściowo z tyłu (b), widoczne wgłębienie przeznaczone na sylikonową poduszeczkę amortyzująca chód robokota, widoczne także położenie dwóch połączeń-*stawów* członów części lokalnej B_{L1} i B_{L2}, Rys. 13 i 14

Fig. 17. The *body* of the final model of the bionic robot *Cthulhu2.0* in the project [8], visualization made in Autodesk Fusion 360 Simulation, view of the model from the top, a proposal for a solution for the moving "*spine*" of the robot visible
Rys. 17. Korpus *ciała* finalnego modelu bionicznego robokota *Cthulhu2.0* w projekcie [8], wizualizacja wykonana w Autodesk Fusion 360 Simulation, widok na model od góry, widoczna propozycja rozwiązania ruchomego „kręgosłupa" robokota

was replaced with the solution shown in Fig. 17. This solution does not allow the robot to adopt such cat poses as the aforementioned bent "*cat's back*". However, it is a good compromise between the cable mechanism and the complete lack of movement inside the body, most often found in other walking robots (*quadropeds*).

Out of all the robot components developed in the project [8], the "*spine*" mechanism was subjected to the smallest number of iterations optimizing its structure topologically and aesthetically.

The last of the *Cthulhu2.0* components presented is the "cat's *head*", the most difficult element in the field of aesthetics, and at the same time the most demanding in terms of the realization of felinotherapeutic benefits that the robocat is to provide. The "*head*" was attached to the body by means of a joint-joint made of two spheres tangent with each other. Provides ±90° mobility of the head swinging. It was also possible to add a universal rotary joint to this structure, running along its own structural axis. This space, however, is intended to accommodate the processor controller and its cabling as well as the drive and movement of the "cat's *eyes* and *eyelids*".

5. Kinematics, kinetics and choice of bionic cat design mechanism drives

The aim of the kinematic and kinetic analysis of the *Cthulhu 2.0* robot mechanism was to verify the correctness of the design and to select the appropriate drive motors. On the basis of the assumed initial parameters of the project, including parameters with constant values, such as, for example, the geometric extent of individual segments of the mechanism, their masses and shapes, and parameters with maximum values, such as velocity and angular accelerations, the forces and moments acting were calculated on individual segments, at their selected points (Fig. 18).

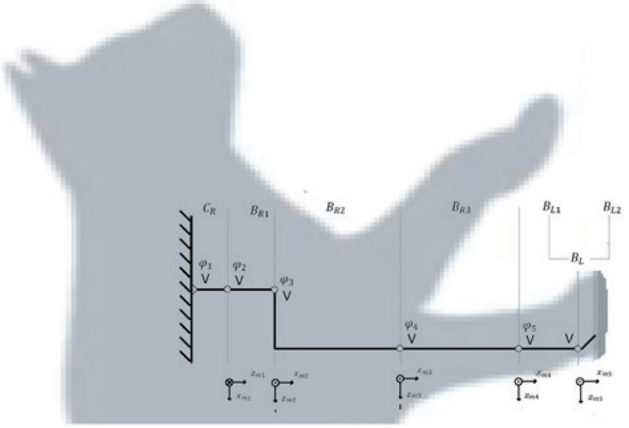


Fig. 18. Simplified, for the needs of kinematic and kinetic analysis and the selection of drives, diagram of the mechanism of the forelimbs of the *Cthulhu2.0* robot bionic model, with five degrees of mobility: upper row of markings, C_R, B_{R1}, B_{R2}, B_{R3}, B_L – counterparts, *shoulder blade*, *shoulder*, *arm*, *forearm* and *wrist* of the cat's front paw; middle row of markings – machine coordinates setting the movement of the robot's mechanism segments; lower order of markings – machine coordinate systems, embedded in the descenting points of individual segments of the robot's limb mechanism

Rys. 18. Uproszczony, dla potrzeb analizy kinematycznej, kinetycznej i doboru napędów, schemat mechanizmu przednich kończyn modelu bionicznego robota *Cthulhu 2.0*, o pięciu stopniach ruchliwości: górny rząd oznaczeń, człony C_R, B_{R1}, B_{R2}, B_{R3}, B_L – odpowiedniki *łopatki, barku, ramienia, przedramienia i kiści* przedniej łapy kota; środkowy rząd oznaczeń – współrzędne maszynowe zadające ruch członów mechanizmu robokota; dolny rząd oznaczeń – maszynowe układy współrzędnych, osadzone w punktach schodzących poszczególnych członów mechanizmu kończyny robokota

In order to simplify the calculations, without generating too much impact on the final results, the geometry of each segment of cat legs was approximated by a cylinder whose length corresponds to the geometric extent of this segment, while the radius and mass were determined on the basis of the 3D *Cthulhu2.0* model (Figs. 7, 9 and 17).

It was decided to apply for this analysis a recursive analysis method perfectly embedded in engineering practice, adapted to the calculations of industrial robot mechanisms, taught at the Faculty of Mechatronics of the Warsaw University of Technology to students of Robotics specialization [15]. This method fits perfectly into the chains of limbs of the designed robot, which are its main subject [8].

Due to the limited volume of the article, it was unfortunately impossible to provide a full analysis. Therefore, it was decided to present only two motors selected for the initial model version of *Cthulhu2.0* and to present the possibility of realizing the maximum values of moment loads resulting from the recursive method of their calculation described below. Readers interested in the extensively complete analysis are referred to the project [8], available at the Central Library of the Warsaw University of Technology.

The following recursive relationships, divided into kinematic and kinetic analysis tasks, were used in the descriped project of *Cthulhu2.0* model, respectively:

- **for kinematic behavior**:
  - the angular velocity of the analyzed segment i in the machine system i of its coordinates

$$\omega_{i/i} = A_{i/i-1}\left[\omega_{i-1/i-1} + \dot{\phi}_i e_{zi-1/i-1}\right], \qquad (5.1)$$

where: $A_{i/i-1}$ – transformation matrix of the coordinate system of the segment i–1 preceding the analyzed segment into the coordinate system of the analyzed segment i; $\omega_{i-1/i-1}$ – angular velocity of the i–1 segment, preceding the analyzed segment, in the i–1 segment system; ϕ_i – assumed maximum angular velocity of the analyzed segment i; $e_{zi-1/i-1}$ – the unit vector z from the segment i–1, preceding the analyzed segment i, in the coordinate system of the segment i–1,

  - the ex-vector matrix of the velocity of the segment i–1, preceding the analyzed segment i, in the coordinate system of the segment i–1

$$\boldsymbol{W}_{i-1/i-1} = \begin{bmatrix} 0 & -\omega_{i-1,zi-1} & \omega_{i-1,yi-1} \\ \omega_{i-1,zi-1} & 0 & -\omega_{i-1,xi-1} \\ -\omega_{i-1,yi-1} & \omega_{i-1,xi-1} & 0 \end{bmatrix}, \qquad (5.2)$$

where: $\omega_{i-1/xi-1}$ – x component of the angular velocity of the segment i–1, preceding the analyzed segment i, in the coordinate system of the segment i–1; $\omega_{i-1/yi-1}$ – y component of the angular velocity of the segment i–1, preceding the analyzed segment i, in the coordinate system of the segment i–1; $\omega_{i-1/zi-1}$ – z component of the angular velocity of the segment i–1, preceding the analyzed segment i, in the coordinate system of the segment i–1;

  - the angular acceleration of the analyzed segment i in the machine system i of its coordinates

$$\varepsilon_{i/i} = A_{i/i-1}\left[\varepsilon_{i-1/i-1} + \ddot{\phi}_i e_{i-1/i-1} + W_{i-1/i-1}\left(\dot{\phi}_i e_{zi-1/i-1}\right)\right], \qquad (5.3)$$

where: $A_{i,i-1}$ – transformation matrix of the coordinate system of the segment i–1 preceding the analyzed segment i, relationship (5.1); $\varepsilon_{i-1/i-1}$ – angular acceleration of the i–1 segment, preceding the analyzed segment, in the i–1 segment system; $\ddot{\phi}_i$ – assumed maximum angular acceleration of the analyzed segment i; $\dot{\phi}_i$ – assumed maximum angular velocity of the analyzed segment I;

$W_{i-1/i-1}$ – ex-vector matrix of the velocity of the segment i–1, relationship (5.2); $e_{zi-1/i-1}$ – the unit vector z from the segment i–1, preceding the analyzed segment i, in the coordinate system of the segment i–1,

– the ex-vector matrix of the velocity of the analyzed segment i, in the machine coordinate system of the segment i

$$\boldsymbol{W}_{i/i} = \begin{bmatrix} 0 & -\omega_{i,zi} & \omega_{i,yi} \\ \omega_{i,zi} & 0 & -\omega_{i,xi} \\ -\omega_{i,yi} & \omega_{i,xi} & 0 \end{bmatrix}, \quad (5.4)$$

where: $\omega_{i,xi}$ – x component of the angular velocity of the analyzed segment i, in the coordinate system of the segment i; $\omega_{i,yi}$ – y component of the angular velocity of the analyzed segment i, in the coordinate system of the segment i; $\omega_{i,zi}$ – z component of the angular velocity of the analyzed segment i, in the coordinate system of the segment i;

– the linear velocity of the $0i$ descending point of the analyzed segment i, in the machine system i of its coordinates

$$v_{0i/i} = A_{i/i-1}v_{0i-1/i-1} + W_{i/i}r_{0i,0i-1/i}, \quad (5.5)$$

where: $A_{i,i-1}$ – transformation matrix of the coordinate system of the segment i–1 preceding the analyzed segment i, relationship (5.1); $v_{0i-1/i-1}$ – linear velocity of the $0i$–1 descending point of the segment i–1, in the machine system i of its coordinates; $W_{i/i}$ ex-vector matrix of the velocity of the analyzed segment i, relationship (5.4); $r_{0i,0i-1/i}$ – the geometrical extent of the segment i (the distance between the segment's ascending and descending points), in its machine coordinate system,

– the square of the ex-vector velocity matrix $W_{i/i}$ $W_{i/i}$, relationship (5.4), of the analyzed segment i

$$\boldsymbol{W}_{i/i}\boldsymbol{W}_{i/i} = \begin{bmatrix} -\left(\omega_{i,yi}^2 + \omega_{i,zi}^2\right) & \omega_{i,xi}\omega_{i,yi} & \omega_{i,xi}\omega_{i,zi} \\ \omega_{i,yi}\omega_{i,xi} & -\left(\omega_{i,zi}^2 + \omega_{i,xi}^2\right) & -\omega_{i-1,xi-1} \\ \omega_{i,zi}\omega_{i,xi} & \omega_{i,zi}\omega_{i,yi} & -\left(\omega_{i,xi}^2 + \omega_{i,yi}^2\right) \end{bmatrix}, \quad (5.6)$$

– the ex-vector matrix of the acceleration of the analyzed segment i, in the machine coordinate system of this segment

$$\boldsymbol{E}_{i/i} = \begin{bmatrix} 0 & -\varepsilon_{i,zi} & \varepsilon_{i,yi} \\ \varepsilon_{i,zi} & 0 & -\varepsilon_{i,xi} \\ -\varepsilon_{i,yi} & \varepsilon_{i,xi} & 0 \end{bmatrix}, \quad (5.7)$$

where: $\varepsilon_{i,xi}$ – x component of the angular acceleration of the analyzed segment i, in the coordinate system of this segment; $\varepsilon_{i,yi}$ – y component of the angular acceleration of the analyzed segment i, in the coordinate system of this segment; $\varepsilon_{i,zi}$ – z component of the angular acceleration of the analyzed segment i, in the coordinate system of this segment,

– the linear acceleration of the $0i$ descending point of the analyzed segment i, in the machine system i of its coordinates

$$a_{0i/i} = A_{i/i-1}a_{0i-1/i-1} + E_{i/i}r_{0i,0i-1/i} + W_{i/i}W_{i/i}r_{0i,0i-1/i}, \quad (5.8)$$

where: $A_{i,i-1}$ – transformation matrix of the coordinate system of the segment i–1 preceding the analyzed segment i, relationship (5.1); $a_{0i-1/i-1}$ – linear acceleration of the descending point of the segment i–1, preceding the analyzed segment in the coordinate system of the segment i–1; $E_{i/i}$ – ex-vector matrix of acceleration of the analyzed segment i, relationship (5.7); $W_{i/i}W_{i/i}$ – square of the ex-vector velocity matrix of the analyzed segment i, relationship (5.6); $r_{0i,0i-1/i}$ – the geometric extent in the coordinate system of the segment i, between the ascending and descending points of the analyzed segment i,

– the linear velocity of the center of mass point C_{mi} in the analyzed segment i, in the coordinate system of this segment

$$v_{Cmi/i} = v_{0i/i} + W_{i/i}r_{Cmi,0i/i}, \quad (5.9)$$

where: $v_{0i/i}$ – linear velocity of the descending point of the analyzed term i, relationship (5.5); $W_{i/i}$ – ex-vector matrix of the velocity of the analyzed segment i, relationship (5.4); $r_{Cmi,0i/i}$ – the geometric extent between the center of mass of the analyzed segment i and the descending point of the analyzed segment i, compare relationship (5.8),

– the linear acceleration of the center of mass point C_{mi} in the analyzed segment i, in the coordinate system of this segment

$$a_{Cmi/i} = a_{0i/i} + E_{i/i}r_{Cmi,0i/i} + W_{i/i}W_{i/i}r_{Cmi,0i/i}, \quad (5.10)$$

where: $a_{0i/i}$ – linear acceleration of the descending point of the analyzed term i, relationship (5.8); $E_{i/i}$ – ex-vector matrix of the velocity of the analyzed segment i, relationship (5.7); $W_{i/i}W_{i/i}$ – square of the ex-vector velocity matrix of the analyzed segment i, relationship (5.6); $r_{Cmi,0i/i}$ – the geometric extent between the center of mass of the analyzed segment i and the descending point of the analyzed segment i, compare relationship (5.9),

– **for kinetic behavior:**

– inertia tensor of the analyzed segment i in the coordinate system of this segment, with respect to the center of mass point C_{mi}

$$\boldsymbol{\Pi}_{i/i}^{C_{mi}} = \begin{bmatrix} I_{xi} & -I_{xyi} & -I_{xzi} \\ -I_{yxi} & I_{yi} & -I_{yzi} \\ -I_{zxi} & -I_{zyi} & I_{zi} \end{bmatrix}, \quad (5.11)$$

with I_{xi}, I_{xyi}, I_{yzi} as moments of inertia of the analyzed segment i in relation to the x axis; y axis; and z axis; I_{xyi}, I_{yzi}, I_{xzi}, I_{yxi}, I_{zyi}, I_{zxi} – as moments of deviation of the analyzed segment i in relation to the appropriate pairs of the x axis, y axis and z axis,

– the force acting on the segment i, coming from the segment i+1, leading the analyzed segment i, transmitted to the segment preceding i–1 (hypothetically the segment driving the analyzed segment i), in the coordinate system of the analyzed segment i

$$F_{i,i-1/i} = F_{i+1,i/i} + m_i a_{cmi/i} - m_i g_{i/i}, \quad (5.12)$$

where: $F_{i+1,i/i}$ – the balancing force in the analyzed segment i the force acting from the leading segment i+1, in the coordinate system of the segment i; m_i – mass of the analyzed segment i; $a_{cmi/i}$ – linear acceleration of the center of mass of the analyzed segment i in this coordinate system, relationship (5.10); $g_{i/i}$ – the gravitational acceleration acting on the analyzed segment i in this coordinate system,

– spiral of the analyzed segment i, in this coordinate system, in relation to the point of its center of mass C_{mi}

$$K_{i/i}^{C_{mi}} = \Pi_{i/i}^{C_{mi}}\omega_{i/i}, \quad (5.13)$$

gdzie: $\Pi_{i/i}^{C_{mi}}$ – the inertia tensor of the analyzed segment i in this coordinate system, with respect to the center of mass point C_{mi}, relationship (5.11); $\omega_{i/i}$ – angular velocity of the analyzed segment i in this coordinate system, relationship (5.1),

- eulerian of the analyzed segment i in this coordinate system, with respect to the point of its center of mass C_{mi}

$$E_{i/i}^{C_{mi}} = \Pi_{i/i}^{C_{mi}} \varepsilon_{i/i} + W_{i/i} K_{i/i}^{C_{mi}}, \tag{5.14}$$

with $\Pi_{i/i}^{C_{mi}}$ – as the inertia tensor of the analyzed segment i in this coordinate system, with respect to the center of mass point C_{mi}, relationship (5.11, 5.13); $\varepsilon_{i/i}$ – angular acceleration of the analyzed segment i in this coordinate system, relationship (5.3); $W_{i/i}$ – ex-vector matrix of the velocity of the analyzed segment i, in this coordinate system, relationship (5.4); $K_{i/i}^{C_{mi}}$ – spiral of the analyzed segment i, in this coordinate system, in relation to the point of its center of mass C_{mi}, relationship (5.13),

- the moment acting on the segment i, coming from the segment i+1, leading the analyzed segment i, transmitted to the segment preceding i–1 (hypothetically the segment driving the analyzed segment i), in the coordinate system of the analyzed segment i

$$M_{i,i-1/i} = M_{i+1,i/i} - R_{cmi,0i/i}F_{i+1,i/i} + R_{cmi,0i-1/i}F_{i,i-1/i} + E_{i/i}^{C_{mi}}, \tag{5.15}$$

where: $M_{i+1,i/i}$ – moment of forces in the analyzed segment i, balancing the momentum of the leading segment i+1, in the own coordinate system of the segment i; $R_{cmi,0i/i}$ – ex-vector matrix of geometric extent (distance) between the descending point of the analyzed segment i and the center of its mass C_{mi}, in the coordinate system of the segment i; $F_{i+1,i/i}$ – force in the analyzed segment i, balancing the force interaction of the leading segment i+1, in the own coordinate system of the segment i; $R_{cmi,0i-1/i}$ – ex-vector matrix of geometric extent between the descending point of the term i–1, preceding the analyzed segment and the center of mass of the analyzed segment C_{mi}, in the coordinate system of the segment i; $F_{i,i-1/i}$ – force acting on the segment i, coming from the segment preceding i–1 (hypothetically the segment driving the analyzed segment i), in the coordinate system of the analyzed segment i, relationship (5.12); $E_{i/i}^{C_{mi}}$ – eulerian of the analyzed segment i in the coordinate system of the segment i with respect to the point of its center of mass C_{mi}.

Both sequences of dependencies (5.1–5.10) and (5.11–5.15) were used in the project [8] for recursive calculation, analysis and simulation of the kinetic behavior of the constructed robot mechanism model.

The key value, which was guided by the selection of the motors, were their nominal moments, adjusted to the calculated maximum torque loading a given segment, needed according to the given dependencies to move with a given speed and acceleration in this given segment.

In designing the mechanisms of conventional industrial robots, this critical moment, needed for the movement of the segments, consists of both the moment coming from the acting forces and moments in the mechanism, and the moment coming from the motor working in the analyzed segment, which drives the next, following the analyzed, segment of the mechanism. The value of this moment obviously depends on the position of this actuator in relation to the machine system of the analyzed segment. Only these two vector-summed moments, loading and motor, are the basis for the selection of the motor for the analyzed segment. The motor placed in the segment preceding the analyzed segment should be selected for this value so as to be able to generate the moment calculated according to the commonly known dependence

$$M_{i,i-1/i\,max} = \frac{M_{i/i-1/?i}^{M}}{\upsilon_{Mi}\eta_{Mi}}, \tag{5.16}$$

where: $M_{i,i-1/i\,max}$ – maximum value of vector-summed moments, loading (5.15) and moment of motor mounted in the analyzed segment i, $M_{i/i-1/?i}^{M}$ – nominal torque generated by the selected drive motor of the analyzed segment i, but located in the i–1 segment, υ_{Mi} – the translation ratio of this motor drive system, η_{Mi} – the efficiency of this motor drive system.

Slightly different than for the mechanisms of conventional industrial robots, the selection of drive motors for the model *Cthulhu2.0* bionic robot mechanism was carried out. Here, the use of tension mechanisms at the junction points of the limb segments relieves not only the volume of these kinematic chains (Figs. 9 and 18), but also in terms of value. Placing the motors in the model's body, between its front and hind limb (Figs. 9 and 17), made it possible to select the motors only on the basis of the calculated, according to the dependence (5.15), loading moments, without taking into account the kinetic behavior of the motors.

In the model version of the *Cthulhu2.0* mechanism described in the publication, Turnigy RC Power Systems motors were used (Tab. 2). The maximum moments loading individual limb segments (Tab. 3) were also compared with the nominal moments

Tab. 2. Catalog data of motors initially selected for the implementation of the model *Cthulhu2.0* bionic robot mechanism [33]

Tab. 2. Dane katalogowe silników wybranych wstępnie dla wykonania modelowego mechanizmu bionicznego robota *Cthulhu2.0* [33]

Name of motor	Turnigy Multistar Brushless Multi-Rotor Motor	Turnigy Multistar Brushless Multi-Rotor Motor
Type	Brushless motor	Brushless motor
Mark	9225-160KV	4112-320KV
Motor view		
Angular velocity in terms of the voltage unit	160 rpm/V	320 rpm/V
Nominal moment	4.83 Nm	2.66 Nm
Energy efficiency	1200 W	660 W
Moment of inertia	$16.6 \cdot 10^{-4}$	$4.1 \cdot 10^{-4}$

generated by their pre-selected motor drives, i.e. the value $M_{i,i\text{-}1/i\ max}$, calculated according to the dependence (5.15), was compared with the value matched to it by the translation $\boldsymbol{\nu}_{Mi}$ value $M^{M}_{i/i-1/?i}$, calculated according to the dependence (5.16).

Tab. 3. Moment loads of limb segments in the model execution of the bionic mechanism of the *Cthulhu2.0* robot [8]
Tab 3. Obciążenia momentowe segmentów kończyn modelowego wykonania mechanizmu bionicznego robota *Cthulhu2.0* [8]

Segment	Front limb	Hind limb
B_{L1}	0.62 Nm	1.83 Nm
B_{R3}	2.86 Nm	4.49 Nm
B_{R2}	5.20 Nm	7.21 Nm
B_{R1}	6.62 Nm	8.82 Nm
C_{R}	8.71 Nm	11.15 Nm

The 4112-320KV motor meets the energy requirements of the B_{L1} (*wrist*) segment only, for the front and rear limbs of the *Cthulhu2.0* model. For the B_{R3} (*forearm*) segment, the energy efficiency of the 9225-160KV motor meets similarly, without translation, its energy requirements. For the remaining segments (*arm, shoulder* and *shoulder-blade*) it was necessary to use a gear ratio. It is possible thanks to the use of linkage mechanisms in the construction of connections of these segments in the mechanisms of the limbs. This resulted in a slight reduction in the speed of movement of the B_{R2}, B_{R1} and C_R segments. In future work on the *Cthulhu2.0* prototype, motors with higher energy efficiency will be selected, meeting the requirements of the kinematic and kinetic analysis of the model. An attempt will also be made to reduce the weight of the motors and the segments themselves by optimizing their shape and choosing a lighter material.

6. Conclusions

The paper describes the development of a concept of a bionic robot that may be used in *felinotherapy* in the future. This task was carried out using the mathematical description of the geometry, kinematics and kinetics of the mechanism of the cat's limbs movement, as well as thanks to the construction of its mechatronic model resulting from the aforementioned analysis. Visualizations and simulations to check the operation of this model were shown. Individual construction elements have been refined in terms of functionality and aesthetics. The materials and components of electronics necessary for the functioning of the model were presented. The concept of robot construction created in this way meets the defined challenges and assumptions and is ready to be tested in practice.

In the project [8], meeting the aforementioned challenges and assumptions, was limited, due to the limited time of its implementation, to printing the most important functional elements of the structure in order to test them under real motion, force, moment and mass (gravity) loads. The share of simulations in design works has also been increased in relation to the originally assumed only model visualizations. Work on motion simulation began with commonly known tools (*Autodesk Fusion 360 Simulation*), but these turned out to be imperfect in a specific case, so the new *PyBullet* programming environment was used, which is definitely more useful and offers excellent possibilities for simulating complex motion mechanics.

When defining the functional assumptions of the robot, it was decided to stick to the standards applicable to cooperative robots (cobots). When selecting the propulsion engines, the challenges of the cat's movement dynamics and its agility were primarily taken into account. In principle, efforts were made to maintain the dimensions of the mechanism corresponding to the *Maine Coon* skeleton, in practice, the selected engines imposed the scale of enlargement of the cat model to the robot model to a value of 1:1.5. Further work envisages a corresponding reduction of the *Cthulhu2.0* model. However, this will not prevent the use of currently selected electronic elements (sensors) and will not hinder the implementation of haptics and meowing actuators important in *felinotherapy* [5].

In the already assumed next stage of robot project development and the development of *Robot Operating System* (*ROS*) software for the control and programming of its movement, it was decided to extend the use of the *PyBullet* environment and the *Python* language for processing data obtained from motion capture cameras into robot movement [2]. The process involves creating an animal anatomical model and mapping key points on it. These points approximate the motion of the animal and move with its model. This allows for the faithful reproduction of the animal's movement, in this case a cat, by the mechatronic bionic mechanism of the robot.

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Innowacyjny koncept budowy robota bionicznego dla zastosowań społecznych w felinoterapii

Streszczenie: W pracy opisano innowacyjny projekt bionicznego robokota dla zastosowań w felinoterapii, wspomagającej szpitalne i domowe leczenie psychoterapeutyczne obłożnie chorych dzieci i dorosłych. Projekt zrealizowano inżyniersko przez biomimikrowanie biologicznego kota, dochodząc do jego robotycznego modelu. Szczególną uwagę w tym procesie poświęcono uchwyceniu istoty kocich zachowań ruchowych i możliwości ich odwzorowania w mechatronicznym modelu. Przeprowadzono analizę geometrii, kinematyki i kinetyki tego modelu, tworząc założenia jego praktycznej realizacji w rzeczywistym mechanizmie kociego ruchu. W wykorzystanym oprogramowaniu korzystano z topologii elementów w obszarze roboczym *Autodesk Fusion 360 Simulation*, wykonując krytyczne elementy mechatronicznego modelu drukiem, w technologii SLS. Prace wspomagano także symulacją graficzną w środowisku *PyBullet*.

Słowa kluczowe: robotyka, bionika, biomimikra, felinoterapia, robokot, modelowanie 3D, mechanizm ruchu, geometria, kinematyka, kinetyka, napędy silnikowe

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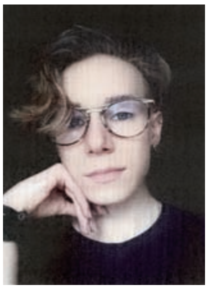

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