

# An Automated System for Analysing Swim-Fins Efficiency

## *Automatski sustav za analizu učinkovitosti peraja za plivanje*

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### Summary

Divers' underwater performance is directly related to their swim-fin efficiency. To determine the efficiency, a comparison is needed between existing models of swim-fins leading to conducting experiments that yield reliable results and promise an optimal model. One method of comparison is to construct an automated system that would be able to mimic human leg movement in a submerged environment during independent experiments. To mimic this human behaviour, the options are to either move the robotic leg in the swimming pool or have water flow around it in a water tunnel. The second mechanism is simpler to construct and develop because it includes fewer mechanical parts and can be built as a stationary test bench. Therefore, this paper reports the development of this mechanism. Its controlling system is designed based on movement patterns obtained using computer vision techniques in addition to analyses of diver's behaviour during initial experiments. The presented solution has the potential for comparing the efficiency of a range of swim-fins in a short time.

### KEY WORDS

automated system  
swim-fin efficiency  
movement pattern

### Sažetak

*Učinkovitost ronilaca pod morem izravno je povezana s učinkovitošću njihovih peraja za plivanje. Da bismo utvrdili učinkovitost, potrebno je usporediti postojeće modele peraja za plivanje, što znači provesti eksperimente iz kojih bi se mogli dobiti pouzdani rezultati i najbolji model. Jedan od načina usporedbe jest izrada automatskog sustava koji bi mogao oponašati pokrete ljudske noge u podvodnome okruženju tijekom nezavisnih eksperimenata. Da bi se oponašalo ovakvo kretanje, opcije su ili pomicanje robotske noge u bazenu za plivanje ili osiguranje protoka vode oko nje u vodenome tunelu. Ovaj drugi mehanizam jednostavnije je napraviti i razviti jer uključuje manje mehaničkih dijelova i može se sagraditi kao statička radna klupa. Stoga se u ovome radu opisuje razvoj takvoga mehanizma. Kontrolni sustav uređen je na temelju obrazaca kretanja prikupljenih uporabom tehnika računalnoga vida, uz analize ponašanja ronilaca tijekom početnih eksperimenata. Predstavljeno rješenje posjeduje potencijal za usporedbu učinkovitosti različitih tipova peraja za plivanje u kratkom roku.*

### KLJUČNE RIJEČI

automatski sustav  
učinkovitost peraja za plivanje  
obrazac kretanja

## 1. INTRODUCTION / Uvod

Swim-fin development, an assurance of better performance for a diver, is of considerable interest. Consequently, a variety of swim-fins, made of different materials and moulded in various shapes, has been constructed [1]–[3], [6]. However, more serious attempts have not been developed to assess swim-fins efficiency. A substantial number of patents, concerning shapes, materials and constructions of swim-fins has been proposed.

The efficiency of a swim-fin also plays an important role in biomimetic underwater vehicles technology [4], [5], [8]–[11]. It results from the fact that an efficient fin can increase the range of a vehicle, which may facilitate reducing its weight and size. Consequently, some research, devoted to developing an optimal swim-fin's shape and flexibility as well as its weight and size has been carried out. Since it is believed that "fish-like" underwater vehicles, equipped with undulating propulsion, could be more efficient than propeller based ones [4], [12], [14], the development of efficient fins will be an essential task.

Even though the efficiency of a swim-fin plays a crucial role in many applications, there has been little attention paid to devise a method that could enable a comparison of different models of swim-fins. What is more, some techniques analyse swim-fin propulsion as a global system, where diver's physiological and biomechanical responses are considered [7]. However, it can lead to erroneous results due to the diver's fatigue during experiments. Therefore, an automated system is needed to carry out reliable tests.

The construction of a robotic system is technically demanding because, in order to consider a large number of determinants, the trial should have regard to the diver's movement. To facilitate it, the test bench, based on moving device in a swimming pool, has been presented in [7]. In this solution, the mechanism reproducing horizontal and vertical motion of the swim-fin is shifted along the side of a swimming pool. Another approach, mainly devoted to the determination of underwater vehicle hydrodynamic coefficients, assumes

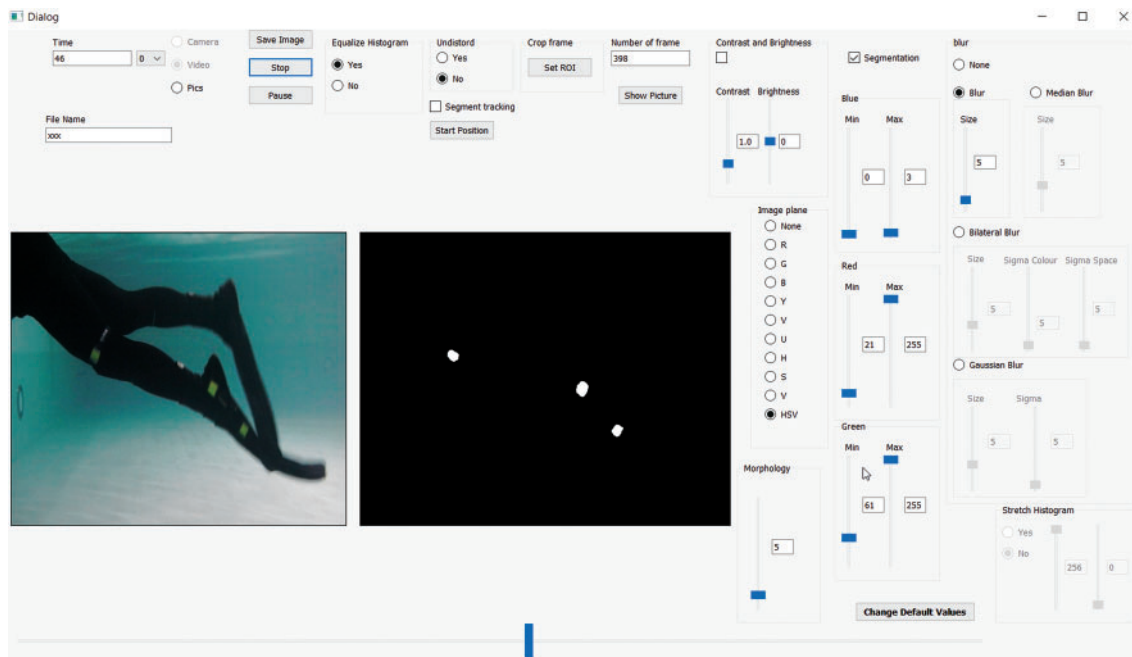


Figure 1 The graphical user interface of the computer application  
*Slika 1. Grafičko korisničko sučelje računalne aplikacije*

that the vehicle is immobile, whereas water flows around it [13]. Since this solution simplifies the construction of the test bench as well as facilitates test performance, it was utilized in this study.

The purpose of this paper is to present an automated system for analysing swim-fins efficiency. In the next section, the movement pattern of a diver's leg, established during preliminary research, is described. The structure of the system as well as software architecture are presented. At the end, results and conclusions are discussed.

## 2. MOVEMENT PATTERN OF A DIVER'S LEG / *Obrazac kretanja noge ronioca*

A genuine pattern of movement of a diver's leg is necessary for developing a control system of the robotic leg. Therefore, to gather necessary data, the experiments with a diver were carried out in a swimming pool. The diver's leg movement was traced using yellow marks placed on the leg. The experiments were conducted for various speeds and different types of fins, which facilitated obtaining representative data. Ultimately, six from all recordings were taken into consideration. Their analyses were performed utilizing a computer vision algorithm, which was designed and implemented into a GUI (graphical user interface) application using the C+ programming language and the OpenCV library (Fig. 1).

The computer vision algorithm, as proposed in the previous work [10], can be divided into the following parts:

- Conversion between the RGB and HSV colour spaces.
- Extraction of yellow pixels representing markers.
- Thresholding.
- Erosion.
- Dilatation.
- Location of obtained blobs in the image.
- Elimination of the false blobs.
- Prediction of locations of the marker in the current image

based on the previous image in case of not detecting the corresponding blob.

Preliminary experiments were conducted in a swimming pool to determine the best method for detecting markers in underwater environments. They proved that the HSV space facilitates better colour detection in the underwater environment than other colour spaces. Consequently, the HSV space allows faultless detection of yellow markers even when light conditions in the swimming pool are changing. The location of the markers on the image is performed by double thresholding with previously established parameters  $Min_{\{H,S,V\}}$ ,  $Max_{\{H,S,V\}}$ , defining the lower and upper threshold. However, after this operation, some random pixels, incorrectly classified as a marker area, were presented on the image. To remedy this, morphological operations erosion and dilatation were applied for removing unnecessary pixels from the pictures. After this step, the likelihood of error still existed; therefore, additional processing to compare markers' location in consecutive frames was developed. In this processing, if the position of the marker significantly differs from the positions of all the detected blobs in the previous image, the marker is removed, and its position is determined using a linear estimator.

The above approach allowed for tracking of the markers in a video stream. Additionally, since an image acquisition rate and all necessary dimensions of the observed scene were known, the following parameters for recorded movies were accessible to calculate:

- Pixel positions of the markers.
- Angles between the arms.
- Angular velocities of the arms.

Exemplary results, obtained with the developed algorithm, are presented below.

A more detailed description of the developed algorithm and an extensive results' presentation and analysis can be found in [10].

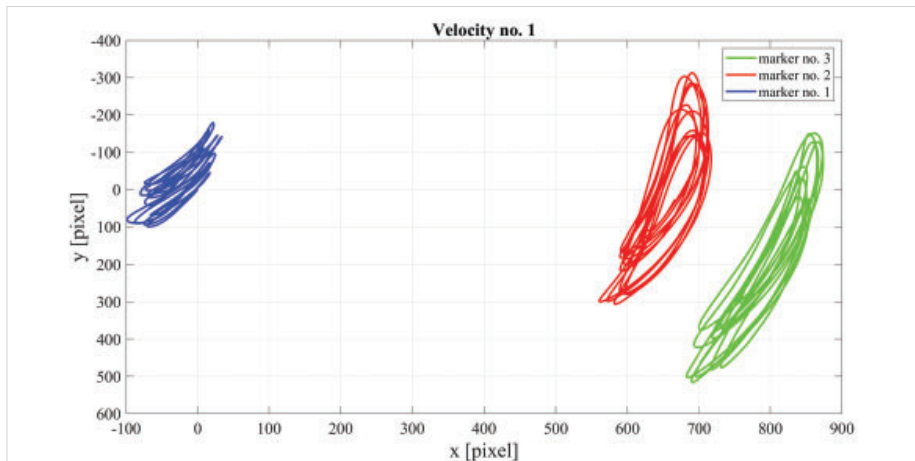


Figure 2 Positions of markers for velocity no. 1 (slow movement)  
 Slika 2. Položaji markera za brzinu br. 1. (sporo kretanje)

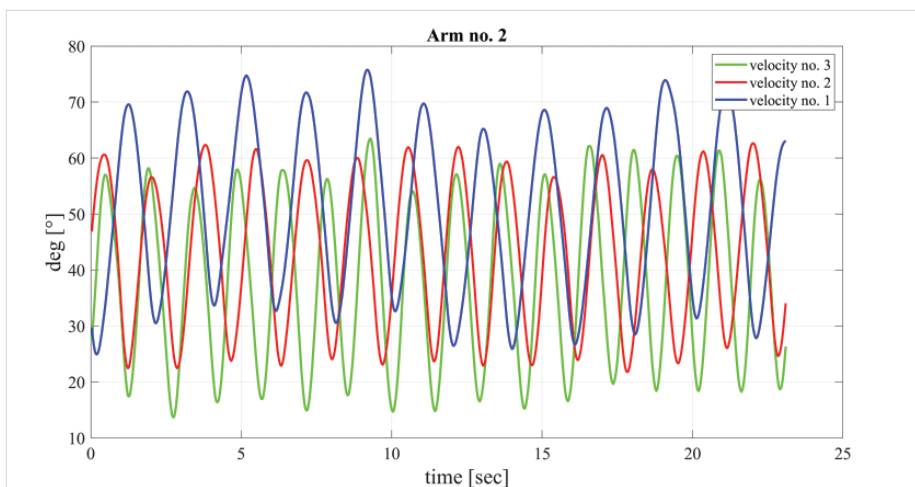


Figure 3 Arm no. 2 angular position  
 Slika 3. Kutna brzina ruke br. 2.

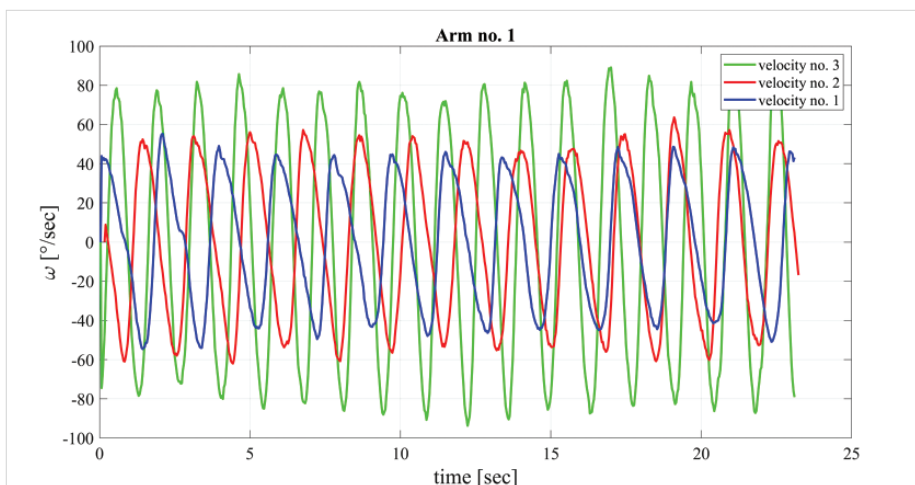


Figure 4 Arm no. 1 angular velocity  
 Slika 4. Kutno ubrzanje ruke br. 1.

### 3. AUTOMATED SYSTEM FOR ANALYSING SWIM-FINS EFFICIENCY / Automatski sustav za analizu učinkovitosti peraja za plivanje

The designed and developed automated system for analysing swim-fins efficiency is depicted in Figure 5. It is composed of two arms, a calf and a thigh, propelled by two motors, and a

foot. The foot's position is controlled by a piston attenuator. The piston attenuator is used to simplify construction and improve the simulation of human animation. The motors are in the upper side of the construction, whereas torque is transmitted through a system of gearboxes to a single articulated joint via V-belt. This construction allows operating motors in the air, while

joints are located underwater and lubricated with flowing water. Consequently, the structure is simplified and more reliable.

In order to operate the leg and carry out necessary measurements, the control and measurement system presented in the Fig. 6 has been developed.

The control and measurement station determines the leg's

position and gathers the necessary data. The leg's position is changed using brushless DC motors supervised by the drive controllers mcDSA-E45 (Fig.7a). The drive controllers are connected to the control and measurement station using the miCAN-Stick2 CAN/USB converters (Fig. 7b). This connection facilitates exchanging data between the station and the controller.



Figure 5 Diver's robotic leg  
Slika 5. Robotska noga ronjoca

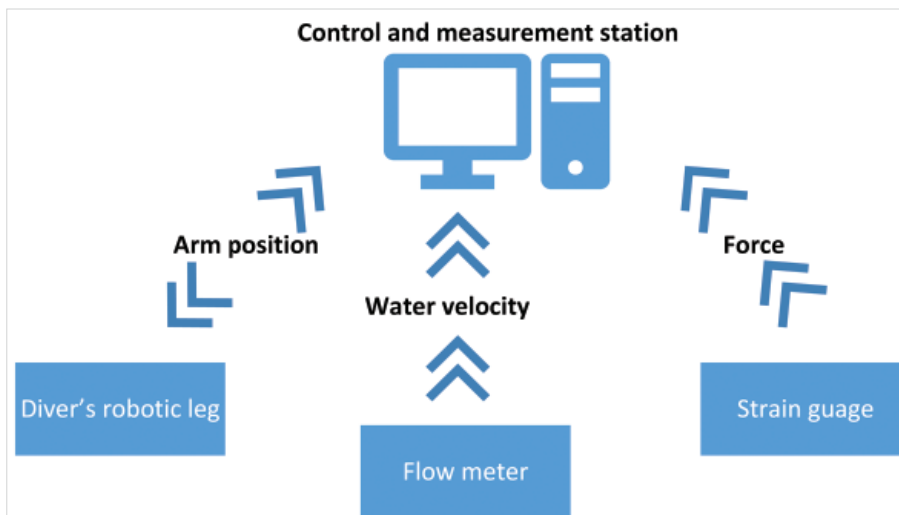


Figure 6 Control and measurement system  
Slika 6. Sustav kontrole i mjerenja



a)



b)

Figure 7 a) Drive controller mcDSA-45, b) miCAN-Stick2 converter  
Slika 7. a) Pogonski upravljač mcDSA-45, b) pretvarač miCAN-Stick2

A strain gauge meter and a flow meter are used in order to collect the data. The strain gauge meter measures thrust generated by the leg, using HBM the PW4C3/300G-1 transducer depicted in the figure below.



Figure 8 HBM PW4C3/300G-1 transducer  
Slika 8. Pretvarač HBM PW4C3/300G-1

The transducer requires a connection to an amplifier; in this work, 1-PAD4001A-RS4 amplifier with RS-485 interface is utilized. As a result, RS-485 to USB converter is needed to facilitate a data transfer between the station and the strain gauge.

In order to measure water flow, an ultrasonic liquid flow meter NFM300M.H was applied (Fig. 9).

Sensors of the flow meter were mounted around the water tunnel, while the transducer was connected to the station via Modbus (serial connection protocol). In this case, the RS-485 to USB converter is also used.

#### 4. SOFTWARE ARCHITECTURE / Arhitektura softvera

A computer application to control the robotic leg as well as to gather and record necessary data was developed using the C++ programming language and the Qt libraries. Consequently,



Figure 9 NFM300M.H ultrasonic liquid flow meter  
Slika 9. Ultrazvučni mjerac protoka tekućine NFM300M.H

it is independent of the operating system, and it provides a graphical user interface (GUI) presented in the figure below.

The user interface facilitates the following operations:

- Manual and automatic control of the leg's position.
- Recording data to a file.
- Taring the thrust value.
- Visualisation of the data on the screen.

The application was divided into three threads; each of them is running on a different core of a processor. The first thread is responsible for communication with a user and control over the other two threads. The second thread enables connection with the motors' controllers, whereas the third one is responsible for data gathering from sensors and writing it to a file. This approach ensures fast data transfer and smooth control of the motors.

The communication with controllers was established using text commands based on the CIA specification DS309-3; this means that each text command consists of keywords and numbers that are separated by spaces. For example, if a new

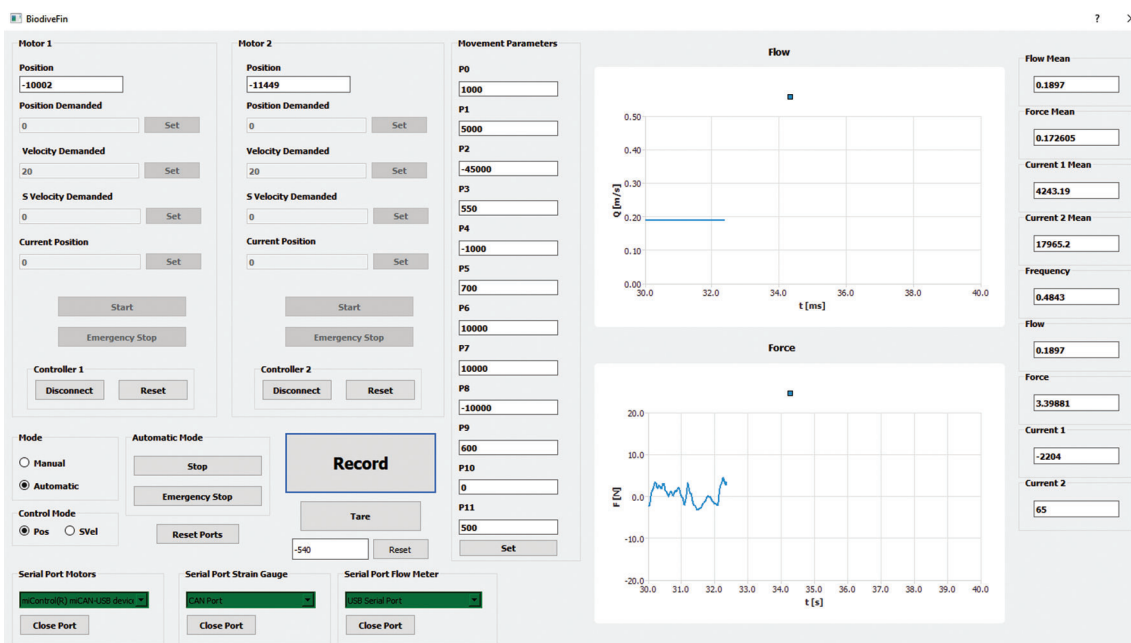


Figure 10 Graphical user interface  
Slika 10. Grafičko korisničko sučelje

arm's position is needed, the following syntax should be used:  
`w m 0x00000201 4 0x00 0x00 0x00 0x00 <CR><LF>`  
 where the last four bytes mean the new position.

One cycle of the communication function includes the following tasks:

- Checking errors.
- Getting data from the controllers.
- Calculating new positions of the arms.
- Sending the new positions to the controllers.
- Waiting 100 ms.

In order to calculate new positions of the arms, the movement pattern of a diver's leg is utilised. However, a direct implementation of the designed pattern was impossible because the driver moved his leg not only in a vertical direction but also in a horizontal one. Additionally, some technical limitations connected with the mechanical construction and the data transmission demanded to develop a new strategy of movement estimation. The mechanical complication results from the fact that belt transmissions of two motors are located on the same shaft. Consequently, the position of the second arm depended on the new position of the first one. The data transmission problem is linked with a delay in data transfer between miCAN-Stick2 CAN/USB and the motors' controllers. It results from the fact that the smooth movement

of the arms requires exchanging data every 100 ms, but the motors achieve the new positions after 1 second. On account of this, the prediction of future legs' positions was designed for implementation in the control system. Consequently, the following algorithm, based on 12 parameters, was developed using the movement pattern and visual examination with a comparison between human and robotic behaviour.

Data collection and recording are executed in the third thread. At the beginning, the communication with the sensors is established. Then, the following loop is executed:

- Sending inquire commands to the sensors in order to obtain measurement data("0x01,0x03,0x00,0x04,0x00,0x02,0x85,0xCA" for the flow meter and "S31;MSV?;" for the strain gauge).
- Receiving and displaying the measurement data.
- Saving obtained data to a file.

The thrust force is obtained in the form of an integer number, which is proportional to the measured thrust. Therefore, a calibration process is required. In this process, the reference curve, depicted in Fig. 11, was obtained. However, although the integer number is proportional to the measured thrust, it is not equal to 0 in the case when the thrust amounts to 0. Consequently, each measurement needs to begin with tarring, necessary to obtain proper data.

```

if (abs(motor_position1 - motor_positionDemanded1) < motor_controlParameters1 && abs(motor_position2 - motor_positionDemanded2) < motor_controlParameters2 && iterationNumber%2 == 1)
{
    motor_positionDemanded1 = controlParameters3;
    motor_velocityDemanded1 = controlParameters4;
    motor_positionDemanded2 = motor_positionDemanded1*0.315-controlParameters5;
    motor_velocityDemanded2 = controlParameters6;//
    iterationNumber++;
}
if (abs(motor_position1 - motor_positionDemanded1) < controlParameters7 && abs(motor_position2 - motor_positionDemanded2) < controlParameters8 && iterationNumber %2 == 0)
{
    motor_positionDemanded1 = controlParameters9;
    motor_velocityDemanded1 = controlParameters10;
    motor_positionDemanded2 = motor_positionDemanded1*0.315 - controlParameters11;
    motor_velocityDemanded2 = controlParameters12;
    iterationNumber++;
}

```

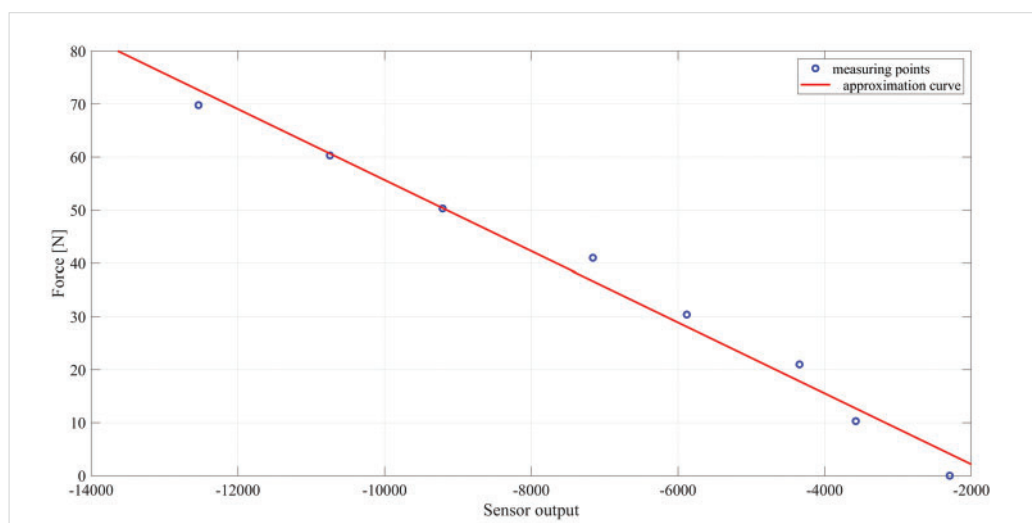


Figure 11 Strain gauge calibration  
 Slika 11. Kalibriranje mjerača napreznja

## 5. RESULTS / Rezultati

As mentioned previously, the aim of the work was to construct a test bench which facilitates conducting experiments in moving water. Therefore, the developed diver's artificial leg was placed in a water tunnel depicted in Fig. 12.



Figure 12 Water tunnel  
Slika 12. Vodeni tunel

The water tunnel was designed to allow laminar flow of water during experiments. The flow was forced using a propeller presented in the figure below.

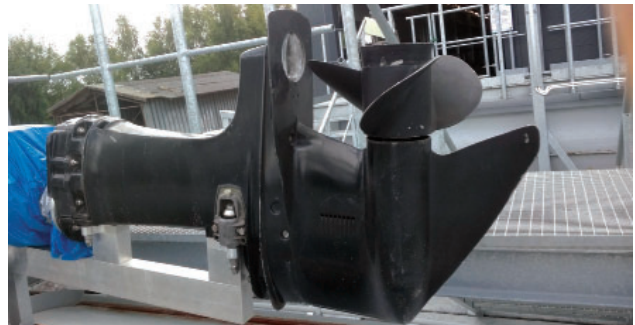


Figure 13 Propeller  
Slika 13. Propeler

In order to design movement models, the movement patterns, as well as qualitative analyses of robotic leg's behaviour, were employed during the initial test. As a result, several movement models for some types of fins were designed. The exemplary movement parameters are presented in Table 1.

Table 1 Movement parameters  
Tablica 1. Parametri kretanja

	Parameters											
	P1	P2	P3	P4	P5	P6	P7	P8	P9	P10	P11	P12
Movement no. 1	1000	5000	-45000	600	-5000	600	10000	10000	-2000	400	0	400
Movement no. 2	1000	5000	-45000	500	-1000	500	10000	10000	-10000	300	0	300
Movement no. 3	1000	5000	-45000	700	-1000	700	10000	10000	-10000	500	0	500

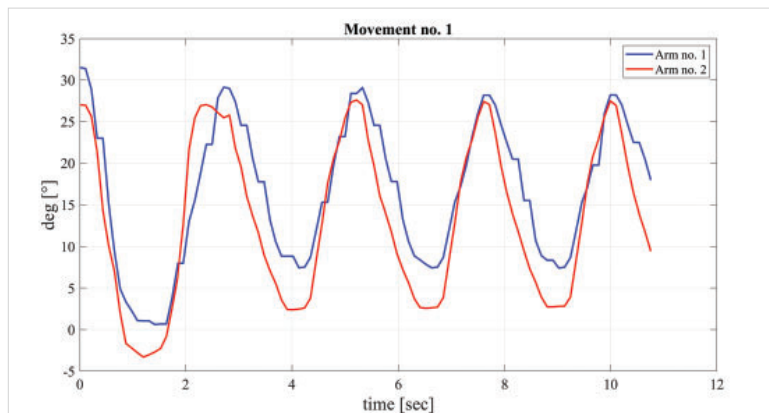


Figure 14 Movement 1 model  
Slika 14. Model kretanja br. 1

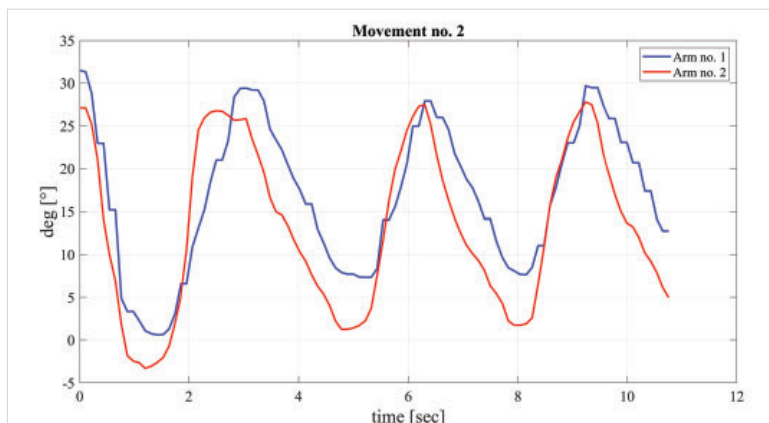


Figure 15 Movement 2 model  
Slika 15. Model kretanja br. 2

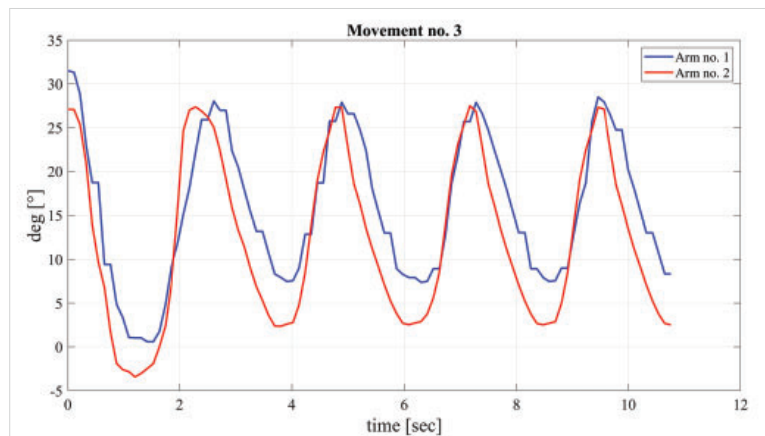


Figure 16 Movement 3 model  
Slika 16. Model kretanja br. 3

The parameters of the first movement were designed for a large fin and fast motion. Figure 14 illustrates the angular positions of the arms during the experiment.

The movement model for the same fin but the slower pace is presented in Fig. 15, whereas Figure 16 illustrates the model for a smaller fin and faster pace.

These results demonstrate that the presented approach facilitates the development of various movement models. However, because of technical difficulties related to a data transfer lag, the movement of the first arm is not as smooth as the second one. Nevertheless, it will not affect future experiments since they will be concentrated on comparative analysis of tested fins.

## 6. CONCLUSION / Zaključak

Prior work has documented the need for developing a method regarding swim-fins efficiencies' calculation and comparison. Because reproducible swimming technique is difficult to obtain due to the diver's fatigue during an experiment, an automated system is desirable to carry out experimentation leading to reliable results. Thus, a test bench that enables carrying out stable experiments in flowing water has been developed in this work.

The test bench has been equipped with a controlling system which has been developed based on movement patterns obtained using computer vision techniques. This solution can be applied for comparing the efficiency of a range of swim-fins. Additionally, the experiments can be carried out for various movement strategies using movement parameters implemented in the control algorithm.

## Acknowledgment / Zahvala

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