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Open E-puck Range & Bearing Miniaturized Board for Local Communication in Swarm Robotics

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Abstract— **We have designed and built a new open hardware/software board that lets miniaturized robots communicate and at the same time obtain the range and bearing of the source of emission. The open *E-puck Range & Bearing* board improves an existing infrared relative localization/communication software library (*libIrcom*) developed for the *e-puck* robot and based on its on-board infrared sensors. The board allows the robots to have an embodied, decentralized and scalable communication system. Its use and capabilities are demonstrated via an alignment experiment.**

I. INTRODUCTION

Ideally, in an autonomous robotics approach, communication systems should provide both situated and abstract communication. Abstract communication refers to communication protocols in which only the content of the message carries a meaning and the physical signal (the medium) that transports the message does not have any semantic properties [1]. Differently, situated communication means that both the physical properties of the signal that transfers the message and the content of the message contribute to its meaning (see [2] for more details). One way to do so is to let the communicating robots extract from the signal the location of the communicating source. Therefore, these systems are commonly called localization and communication systems. In our research we are interested in creating useful tools in the domain of localization and communication systems, providing situated and abstract communication for groups of autonomous cooperating robots.

Several research works have focused on the development of localization and communication systems. Many of these works are emulations of relative positioning systems, and in some cases the systems are developed and tested only in simulation. Roumeliotis and Bekey [3] proposed the use of a Kalman Filter to combine dead reckoning and information from an emulated relative positioning system to allow a group of mobile robots to solve the issue of localization. Ludwig and Gini [4] used a wireless local area network to let a robotic swarm disperse to cover an unknown area. In this study, one robot was required to be stationary to determine distance and bearing information. However, the use of wireless networks usually implies experiments with long range communication. Although using radio communications for relative localization without any external fixed beacon can be achieved, it is necessary to use a high frequency system combined with the use of directional antennas to accomplish the same resolution as with ultrasonic or infrared technologies. This implementation results in a too big and expensive solution for being implemented in small size boards. An ultrasonic localization system is described in [5] making use of radio components that increase the power consumption and the board cost. On the other hand, [6], [7] accomplished a very accurate relative positioning using ultrasound, but tests were never performed with more than two robots and the minimum transmission range was 0.5 m. The use of ultrasound suffers from echo effects and interference that reduce the performance when more robots are introduced in the system. Another problem is that the aperture angle of the ultrasonic emitters is not narrow enough to achieve a good directionality.

Because of the above-mentioned limitations, the use of infrared signals seems to be the most promising approach for the development of localization and communication systems [8]. This approach has already been studied by [9], [10], and more recently by [11]. However, these works are either implemented in big size robots and electronics has not been miniaturized, or the information available is not enough to replicate them in other robots.

In this paper we describe an open miniaturized local communication module (i.e., *E-puck Range & Bearing*) for a miniaturized open hardware/software robot which will allow researchers to replicate and build the system by themselves. The communication system implemented is based on technologies developed for computing relative distance and bearing of infrared signals' sources. The work adapts a previous system [12] to the *e-puck* robot. The system used manages transfer and processing of signals in software with a specific additional hardware. The *E-puck Range & Bearing* board obtains the localization of the signal source by exploiting the physical properties of the signals and the morphology of the robots. Messages can be sent in specific directions and receiver robots can identify the physical location of the signal source. Sent messages remain anonymous and are not exclusively perceived by one target robot. Our robots are therefore endowed with both abstract and situated communication capabilities.

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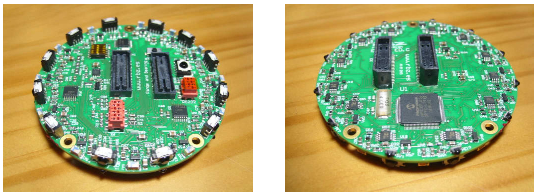
II. RANGE & BEARING BOARD

A. The Platform

E-pucks are modular, robust and non-expensive robots designed by Francesco Mondada and Michael Bonani from *Ecole Polytechnique Fédérale de Lausanne* (EPFL) for research and educational purposes [13]. They are small wheeled cylindrical robots, 7 cm of diameter, equipped with a variety of sensors, and whose mobility is ensured by a differential drive system. *E-pucks* are powered by a dsPIC processor and feature a large number of sensors in their basic configuration. The *e-puck* hardware and software are fully open source[1] providing low-level access to every electronic device and offering extension possibilities. *E-pucks* are equipped with 8 infrared proximity sensors, a 3D accelerometer, a ring of 8 LEDs and a CMOS camera. Extension boards communicate with the main board through an I2C, SPI or RS232 bus. Finally, Bluetooth communication is available for programming the robot and communicating data to a computer or to other Bluetooth devices.

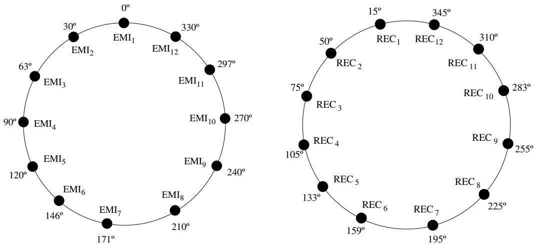
Previous works in communication implemented an extension board based on Zigbee technology [14] to remove the Bluetooth limitations. Although this new board allows wireless communication between the robots, the implementation of a local localization system is not possible. For supplying this missing functionality a software library (*libIrcom*) was developed. *LibIrcom* is a library that can be used straightforward on the *e-puck* robots to achieve local range infrared communication [15]. *LibIrcom* relies on the infrared sensors of the robots to transmit and receive information. The communication system is multiplexed with the proximity sensing system commonly used on the robots. It is therefore possible to both communicate and avoid obstacles. *LibIrcom* allows communication at a rate of up to 30 bytes per second from sender to receiver, including a 2 bits CRC check in each byte to detect erroneous messages. Messages are encoded using frequency modulation that permits usage in a wide range of light conditions. Messages can be detected at a distance of up to 25 cm between the emitter and the receiver.

Although this library is a big achievement considering the characteristics of the robot, several limitations make the library insufficient for many multi-robot scenarios. On one hand, the main processor must execute the communication modulation/demodulation of the eight sensors with a high priority level, which limits the computational resources that remain available in the robot processor. Additionally, signal emission is made in opposite sensor pairs due to the robot design, so it is not possible to transmit different data in different directions. On the other hand, since the sensors used to communicate are the same as those used for proximity readings, an accurate timing must be carried out for the robots' movement. Finally, due to the main processor limitations and the analog to digital converters, once the preamble of a message starts to be decoded by the robot, the processor must focus on a specific sensor and inhibit the other seven sensors inputs. The *E-puck Range & Bearing* was designed to remove these limitations and in particular to (i) increase the range of transmission, (ii) free the main processor from the tasks of modulation and demodulation, (iii) have the different communicating sensors work in parallel, and (iv) increase the communication speed.



(a) (b)

Fig. 1. *E-puck Range & Bearing* board (a) top view (b) bottom view.



(a) (b)

Fig. 2. *E-puck Range & Bearing* board (a) emitters location (b) receivers location.

B. The Hardware

The *E-puck Range & Bearing* board has been modified and updated from a previous design [12] to adapt it to the *e-puck* robot[2]. Even though the original electronics on the board allowed ranges of transmission of up to 6 m, range has been limited to 80 cm due to the robot size. Moreover, the board firmware has been redesigned to improve the range and bearing measures. The board (See Figure 1) is controlled by its own processor, freeing the robot's main controller. Each board includes 12 sets of IR emission/reception modules. Each of these modules is equipped with one infrared emitting diode, one infrared modulated receptor and one infrared photodiode. The modules are nearly uniformly distributed in the perimeter of the board; so, the distance between them is approximately 30° (see Figure 2).

The board has an isolated power supply, dedicated to the transmission module, whose voltage can be varied using a linear regulator. In this way the board can modify its emission range by changing the polarization of the emitting diodes. Ranges from 0 cm to 80 cm can be software controlled by the robot's main board by adjusting the power supply. The power consumption of the board starts from 74 mW when there is no transmission to reach a maximum value of 121 mW.

A frequency modulated transmission at 455 KHz is generated by a timer on the main processor modulating data

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[1] Further details on the robot platform can be found at http://www.e-puck.org.

[2] For an exhaustive description of the board and the complete hardware and software sources see http://www.rbz.es/epuck/.

at 10 KHz. A message is made of 4 bits of preamble, 16 bits of data and 4 bits of CRC, using a Manchester encoding. Therefore, the maximum theoretical frame rate is approximately 208 messages/second.

The reception modules are in charge of getting the data with the infrared modulated receptor. Range and bearing are estimated using a peak detector associated to each modulated sensor.

The board communicates with the robot through an I2C bus or a serial port (UART), depending on the needs of the user, and the robot's resources used in other extension modules.

C. The Software

Once the board is initialized, different modules start running in parallel. The 455 KHz signal is managed through a PWM timer which is never stopped. The I2C and UART interrupts are started waiting for the robot commands. Finally, a timer in charge of the reception module is started.

1) The communication: If the communication with the main board is based on the I2C bus, the bus is shared with other different existing extensions boards. In this case, the board acts as a slave waiting for the commands of the robot and the robot must check if the board receives any new frame.

If the communication with the main board is based on the UART, the board and the robot communicate through interruptions. In this case the robot is freed from asking continuously to the board, as the board will transmit the data when they arrive.

In both communication types, the robot has to set up the maximum transmission distance.

2) Transmission Module: As discussed in section II-B, there are 12 different transmission sensors. Three different types of transmission can be asked to the board: *(i)* All the sensors transmit the same data and produce an omnidirectional communication, *(ii)* only some sensors transmit the same data and *(iii)* different sensors transmit different data.

Once the data are prepared, the board is in charge of decomposing the data and creating a queue with the preamble, the data and a CRC. Since the distance and angle reception is managed by the peak detector, a similar power transmission level is desirable for any data sent. To comply with this restriction, the communication is based on a Manchester encoding. The board is able to obtain data transmitted from different sources of emission at different orientations at the same time. Therefore, no collision model has been implemented to arbitrate between multiple robots transmissions.

3) Reception Module: When a reception frame is received the board checks if it is correct using the CRC. If it is correct, the board reads the peak values and stores them. As different sensors can receive the same data at the same time, due to the aperture angles of the receptors, a data processing must be applied to the received values. We have modified the original processing model to a more accurate one, presented in Section II-D.

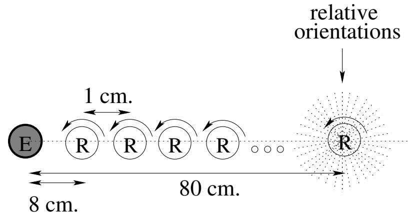


Fig. 3. Physical arrangement of robots for the modelling tests. Figure not to scale.

D. Localization Data Processing

A number of tests have been run to characterize the localization and communication system. One emitter and one receiver robot are placed in an obstacle-free arena from 8 cm to 80 cm, in 1 cm interval as shown in Figure 3. The emitter stays in place while the receiver spins at a 10 ° interval. At each position, the receiver waits till 100 messages are received and stores the values from the 12 sensor peaks. If data is not received in some sensors, the value is 0. We have repeated this test for 36 angular position, 72 linear positions and 10 different *E-puck Range & Bearing* boards. Figure 4a shows an example of all the sensors values for different distances at the same angular position of 110 °, while Figure 4b shows an example of the sensors' map for different angles at the same distance of 9 cm. Although data transmission is achieved for distances of up to 80 cm, distance values farther than 53 cm are not distinguished by the peak receptors, as observed in Figure 4a. In this case the board returns the data with a value indicating that the emitter is too far.

To obtain the values of the range and bearing we start with the calculations of the bearing. A vector sum is implemented for the bearing calculations following Equation 1:

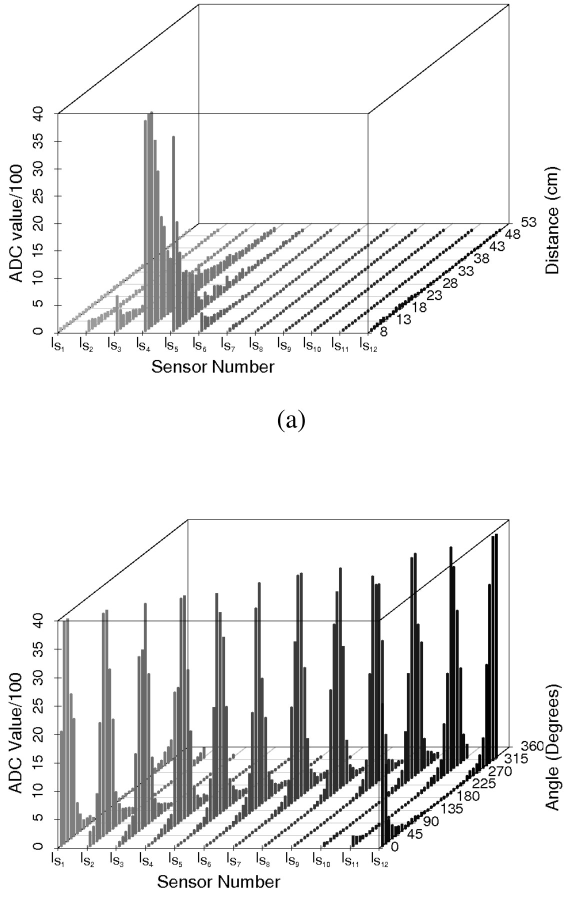
$$\widetilde{\phi} = arctan\left(\frac{\sum_{i=1}^{12}\widehat{\nu}_i cos\left(\beta_i\right)}{\sum_{i=1}^{12}\widehat{\nu}_i sin\left(\beta_i\right)}\right) \tag{1}$$

where $\widetilde{\phi}$ is the estimated bearing with respect to the robot's heading, β_i is the angular distance between sensor i and the board's heading and $\widehat{\nu}_i$ is the value received on sensor i.

Once the bearing is calculated we proceed to calculate the estimated distance to the source. The angle calculated previously determines if the emitter is facing perfectly a receiving sensor or if it is in between two sensors. In any case, following the calculations of [11], we obtain a correction of the received power value as follows in Equation 2:

$$\widetilde{\nu} = \left(\left(\frac{\widehat{\nu}_l}{\sqrt[2]{\cos\theta_r}}\right)^4 + \left(\frac{\widehat{\nu}_r}{\sqrt[2]{\cos\theta_l}}\right)^4\right)^{\frac{1}{4}} \tag{2}$$

where $\widetilde{\nu}$ is the estimated range to the emitter, $\widehat{\nu}_l$ and $\widehat{\nu}_r$ are the values received on the left and right sensor from the estimated angle respectively and θ_r and θ_l are the angular



(a)

(b)

Fig. 4. Sensors' map for (a) different distances at a relative orientation of 110 ° (b) different orientations at a distance of 9 cm.

distances between the estimated angle $\widetilde{\phi}$ and its left and right nearest sensor respectively.

With this model at hand, we have programmed the *E-puck Range & Bearing* board, and repeated the experiments for 10 additional boards. We calculated the error for each measure of range and bearing of the receiving robot over all ranges. The bearing error average across all angles and distances is 4.32 ° and 12.32 ° in the worst case. The range error average across all angles and distances is 2.39 cm and the worst case is 6.87 cm.

III. PROOF OF CONCEPT

We decided to test the effectiveness of the board using an alignment task. This task has been previously solved using evolutionary robotics techniques [15] with the *libIrcom* library. We wanted to test the effectiveness of the new board and the improvements with respect to the previous implementation. In this task, robots should align exploiting the board capabilities. Alignment is a fundamental behavior for a number of tasks in robotics such as cooperative transport or flocking [16], [17], [18]. The experimental setup consists of a group of homogeneous *e-pucks* that are positioned in a boundless arena at a distance of 15 cm from each other, with randomly generated initial orientations, as depicted in Figure 5. Each agent can only change its orientation through rotational movements. The robots can not move away or approach each other, they can only turn on spot. The robots should converge to a common arbitrary direction by exploiting the properties of the communication system, that is, the *E-puck Range & Bearing* board.

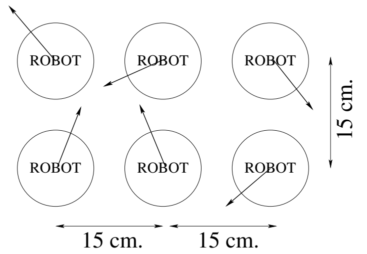


Fig. 5. Physical arrangement of a group of 6 robots for the tests.

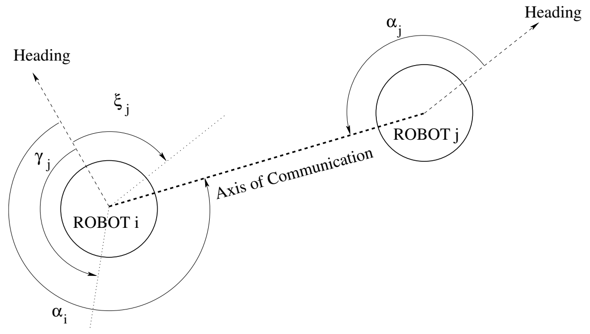


Fig. 6. Robots sharing information about their relative orientations.

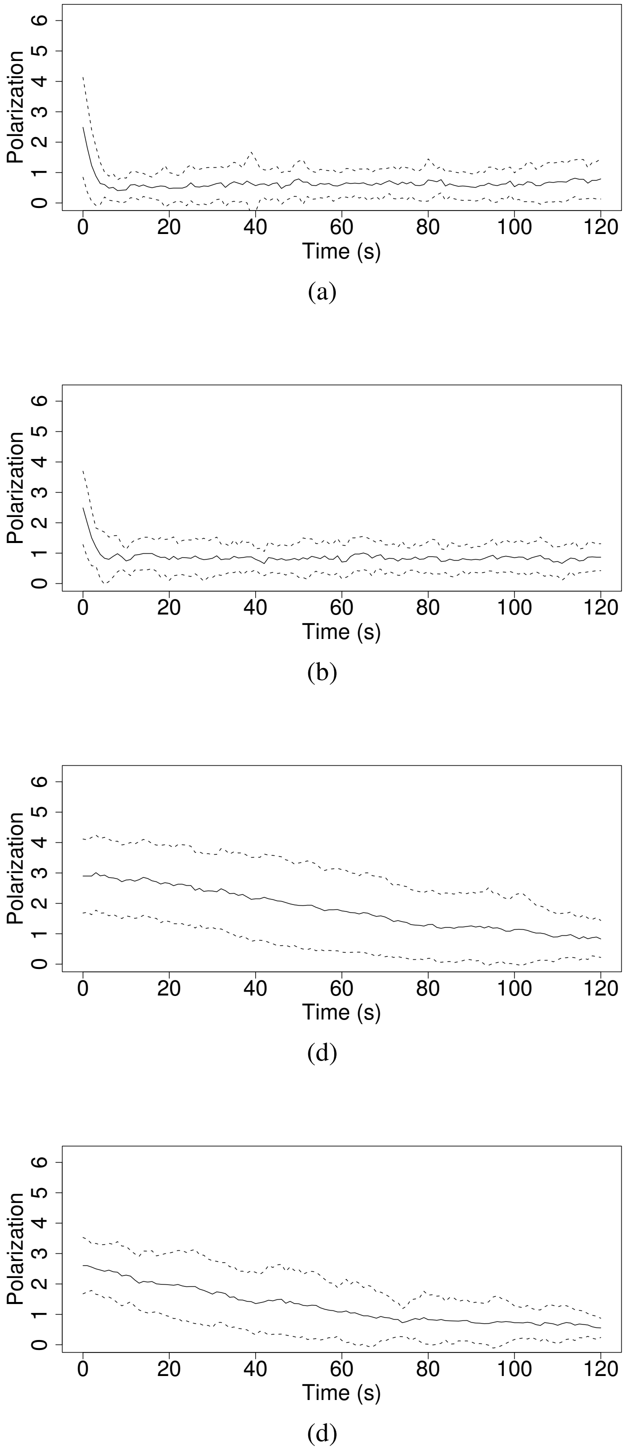
Robots do not have any common global reference system so they can only communicate the orientation as a relative measure to each other. In this case the common element is the axis of communication (see Figure 6). In a first step, robot i transmits a broadcast frame. Subsequently, robot j understands that there is a neighbor at angle α_j and communicates its relative orientation α_j. In a second step, robot i transforms the received data $(\gamma_j = \alpha_j)$ into its own coordinate system. It calculates the direction pointed by robot j as $\xi_j = \gamma_j + \alpha_i - \pi$. Following this communication, the robots will both rotate gradually towards a common direction. The robots regularly communicate to update their information about each other orientation. Eventually, the robots point towards a common direction and are aligned.

Experiments are recorded using a digital camera. A tracking software is used to automatically extract the heading of each robot at each second. We use a specific measure of polarization to calculate the degree of alignment of all the robots. The polarization $P(G)$ of a group of robots G is defined using the notion of angular nearest neighbor. For a robot r, the angular nearest neighbor c is defined so that θ^{rc}, the relative orientation of c with respect to r, is the smallest possible : $\theta^{rc} < \theta^{ri}, \forall i \in G \setminus \{c\}$. We denote $\theta_{ann}(r)$ the relative orientation of the angular nearest neighbor of robot

r. The formal definition of polarization is as follows :

$$P(G) = \sum_{i \in G} \theta_{ann}(i). \tag{3}$$

If all robots are aligned, then $P(G) = 0$. Conversely, if robots are completely misaligned, $P(G) = 2\pi$. Lastly, if headings are random, that is, drawn from a uniform distribution, then the expected value of $P(G)$ is π. It is worth mentioning that meaningful comparisons between different group sizes are possible since the average value of $P(G)$ is not affected by the number of robots in G.



(a)

(b)

(d)

(d)

Fig. 7. Mean polarisation (± standard error) in function of time for 30 repeated experiments. (a) 2 e-pucks, (b) 3 e-pucks, (c) 4 e-pucks, and (d) 6 e-pucks.

We tested the algorithm in groups of 2, 3, 4, and 6 e-puck robots. Figure 7 reports the average polarization (± standard error) of the robots across 30 repeated experiments. We have observed very good alignment for groups of 2 and 3 robots. For these group sizes, the polarization measure is not statistically different. Groups of 4 and 6 robots are less performant and need more time to achieve alignment.

Figure 8 clearly shows that groups converge and maintain their alignment till the end of the experiments.

To summarize, results show that the new board has been successfully plugged in the robots to carry out the experiment. The algorithm implemented is able to cope with different group sizes and exhibits graceful degradation of performance as the task becomes more difficult. Notice that no sharing medium control systems have been implemented. This is not necessary as the possibility of reducing the range of transmission allows the robots to not flood the environment with infrared signals. The use of the board for the alignment task shows better results than those previously obtained with *libIrcom* [15]. Thanks to the speed and accuracy of the range and bearing communication system, the time needed to observe group alignment has been reduced from 150 s to 10 s in groups of 2 and 3 robots, and from 250 s to 80 s in groups of 4 and 6 robots.

IV. CONCLUSIONS

In this paper we have described and tested a board for localization and local communication in robotics. We have modified and adapted a previous existing board specifically for miniaturized multi-robot systems.

The system provides a communication rate of 5 kbps with frequency modulation. The communication range varies from 0 to 80 cm and can be software adjusted in real time. The system can simultaneously receive data and extract range and bearing from a communication. It is also able to receive and transmit data from/to different directions at the same time, while simultaneously identifying the location of several

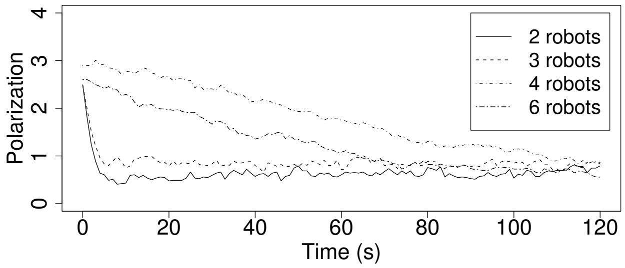


Fig. 8. Mean polarisation for 30 repeated experiments for all group sizes tested (2, 3, 4, and 6 e-pucks). Standard errors are not shown for the sake of clarity.

sources of emission.

Moreover, a robotics task has been carried out and the board has been tested in a real experimental situation. The alignment task studied previously has been reproduced in order to observe the benefits of using the new hardware over a software solution.

The authors provide this board under an open hardware/software license which allows the robotics community to replicate, change and adapt the board to their needs.

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