BioMechatronic Design and Control of an Anthropomorphic Artificial Hand for Prosthetics and Robotic Applications

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***Abstract* – The paper proposes a biomechatronic approach to the design of an anthropomorphic artificial hand. The hand is conceived to be applied to prosthetics and biomedical robotics; hence, anthropomorphism is a fundamental requirement to be addressed both in the physical aspect and in the functional behavior.**

As regards the hand mechanics, a cable-driven underactuation is proposed in order to enlighten the structure, allow anthropomorphic self-adaptation to the object to be grasped, and simplify the control. Two simple PD control systems are formulated and evaluated in a common task of grasping a cylindrical object. The reference input for the control is derived from data on human subjects performing the same task and extracted by the literature. The paper reports simulation results about the comparison with the human case when both control systems are used to close the finger, so to derive specific indications for the improvement of the hand design.

***Index Terms* – Biomechatronic prostheses, Bio-robotics, Prostheses control systems**

I. Introduction

The human hand is composed of bones, muscles, ligaments, tendons, veins, arteries and nerves that let it make complex movements and multiple functional tasks. It contains about 26 bones and 19 muscles and, thanks to its nerves and receptors, it is very sensitive. Bones are connected each other by means of articulations and can flex, extend, abduct and adduct. Muscles are grouped into intrinsic muscles, that are in the hand, and extrinsic muscles, that are in the forearm and are connected to the fingers by tendons. The number of bones and articulations, the powerful and accurate musculature and the highly sensitive epidermis make the hand a smart, complex motor organ. The hand can feed back information to be used for its own functioning and for improving knowledge on the environment; thanks to the hand, the brain can appreciate the texture, the volume, the weight and the temperature of an object. In order to alter nature and to distinguish from other species, the hand-brain interaction is essential for the human: without the hand, the human idea of the world would be flat [1].

In brief, the human hand represents a wonderful example of natural biomechatronic system which robotic designers aim at replicating [2,3]. In the literature several examples of robotic hands can be traced, ranging from simple grippers for industrial applications up to more sophisticated mechanics trying to imitate human mechanics [4,5,6,7]. However, some requirements continue to be unsatisfied. This is mainly due to the lack of a natural interface (with the Peripheral or Central Nervous System (PNS or CNS)) and of light and powerful actuators.

Generally, end effectors of industrial robots are simple grippers or specific tools able to perform stable grasp of heavy objects. They are purposively designed for a specific task and have low manipulation capability. However, to execute different complex tasks, adaptability and versatility of the end effector are essential requirements. Thus, the design and development of anthropomorphic robotic hands is growing popularity also in the industrial field.

At the same time, humanoid robotics is one of the fields spending significative efforts in designing artificial anthropomorphic hands. This is because the humanoid robot has to achieve performance as close as possible to humans, trying to replicate them from the viewpoint of sensori-motor coordination as well as of prompt reaction to variable unstructured environments.

Prosthetics was one of the first application fields for artificial anthropomorphic hands, for aesthetical as well as functional reasons. Prosthetics involves a series of hard requirements regarding the physical aspect, the encumbrance, the weight and the control simplicity, which are in general difficult to satisfy. This is the main reason for the simplicity of the actual commercial prosthetic hands. They are basically simple grippers with few degrees of freedom (DoFs), a reduced natural aspect and actuators able to exert high grasping forces [8]. They still present a

series of inconveniences related to the reduced functionality and controllability.

This paper is focused on the biomechatronic approach to the design and control of an anthropomorphic artificial hand [9] which could represent an innovative platform for robotic as well as prosthetic applications (Fig. 1). In order to answer the basic requirement of control simplicity without compromising functionality, the hand is conceived to self-adapt to the object shape. This is obtained by means of an underactuated cable-driven mechanism for each finger, which allows moving three phalanges through a unique actuator. The cable is lodged in the finger in order to allow phalanges to continue moving even when one of them comes into contact with the object.

In view of the anthropomorphic aspect of the biomechatronic hand, the design of the control system is aimed at replicating human behavior in closing the hand finger while grasping an object [10]. Hence, the authors have borrowed from the literature data on the human behavior during reaching, particularly the tip and joint behavior [11,12], and used them to provide a trajectory reference to the control system. The design of the control system for the biomechatronic hand tries to respect the priority target of a good trade-off between simplicity and functionality, in accordance with the peculiarity of the actuation system. To this regard, the authors have focused their attention on the PD control plus gravity compensation [13, 14], by adapting it to the underactuated structure. In particular, they have developed two different versions of the control system, one in the joint space and the latter in the slider space, in order to compare their performance.

Simulation tests are reported in this paper in the case of one finger motion while closing in absence of gravity. Results related to the two control systems are based on the assumption of planar grasp of a cylindrical object.

It is foreseen that simulation results will be used for further refinements of the hand design in the next steps of this research effort.

II. THE BIOMECHATRONIC DESIGN

A. Design approach

The biomechatronic design approach is based on the analysis of the morphological and functional characteristics of the human hand. In particular, requirements for the design and development of the artificial hand are extracted from the study of the human hand [1] from the viewpoint of anatomy, gesture and grasping capabilities, kinematic and dynamic performance.

Some functional requirements of the human hand can be summarized as:

- Reaching and pre-shaping
- Grasping
- Manipulation with stable grasp
- Exploration with sensori-motor coordination
- Gesture expressiveness.

Hence, the actuation finger mechanism as well as the type of sensors were chosen in order to address the requirements coming from the anthropomorphism and also from the application field (robotics or prosthetics).

The virtual prototype was built using Computer Aided Design tools. These allow studying artificial hand kinematics and dynamics and verifying respondence to the initial requirements. In case of unsatisfied requirements, mechanical features of each component and, consequently the virtual prototype, can be modified.

Also, interaction forces among the components can be estimated. The forces are used as input data for the structural analysis and, if one component is not able to sustain external loads, the hand is redesigned. In this way, the design process is cyclically repeated in order to optimize the hand. The final virtual prototype will satisfy the initial requirements and its kinematics, dynamics and structural characteristics will be well defined. The design flow ends with the technical drawings of each mechanical component (Fig. 1).

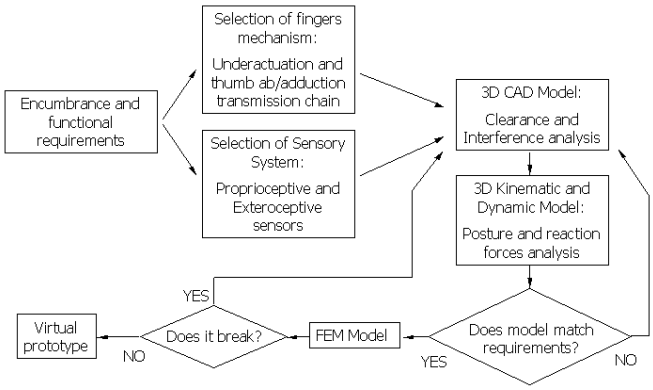

Fig.1 The biomechatronic design flow.

The hand dynamic modelization and the design and development of the control system will contribute to further optimize the choice of the fundamental mechanical parameters.

B. The underactuated artificial hand

The artificial hand is composed of three underactuated fingers (index, middle and thumb) which are actuated by three DC motors placed in the lower part of the arm (e.g. the socket for an upper prosthetic limb or the robotic arm for a robotic artefact), reproducing the principle of extrinsic muscles (Fig. 1). The current hand prototype is an evolution of the RTR II prosthetic hand [15].

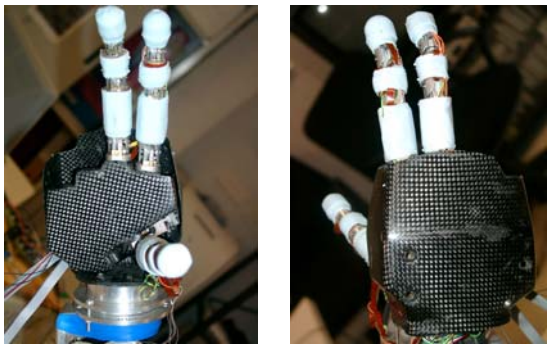

Fig. 2 The three fingered artificial hand.

Three fingers can be considered the minimum in order to have a stable grasp, decreasing the hand weight. To satisfy aesthetic requirements, the hand can be covered with a silicone glove that includes the ring and little passive fingers.

Each finger can flex thanks to a cable which runs along its volar side and wraps around idle pulleys placed in each joint according to the Soft Gripper mechanism [16] (Fig. 3).

The hand is able to adapt itself to the object shape thanks to the cable finger mechanism [17].

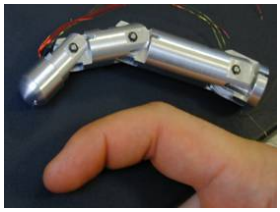

Fig. 3 The artificial finger mechanical structure close to the human finger.

The thumb can abduct and adduct moving from the palmar position to the lateral position and vice versa (Fig. 4). The DC motor used to generate the ab/adduction motion is placed inside the palm and can rotate the thumb through a worm wheel gear mechanism. It is not a backdrivable device, so the thumb can fix its position when the power is off.

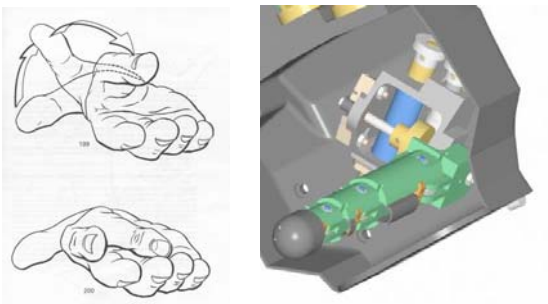

Fig. 4 The abduction and the adduction of the human thumb and the 3D CAD model of the artificial thumb mechanism.

The artificial hand has 10 Degrees of Freedom (DoFs) and 4 Degrees of Motion (DoM): 1 DoM/3 DoFs for each finger (flexion/extension) and 1 DoM/1 DoF for thumb opposition (adduction/abduction).

The palm is composed of three components (that are the outside shell, the inside frame and the inside shell) made of carbon fiber. This material conveys to the structure high strength and light weight. The fingers are made of aluminium alloy (2011 Aluminum Speedal) and have a cylindrical shape in order to optimize the grasp and the contact point with the object.

The artificial hand performance is reported in the following:

- weight: 320 gr
- dimensions: 191 x 95 x 40 mm (length x width x thickness)
- maximum cylindrical grasping force: 35N
- maximum tip to tip grasping force: 15 N
- maximum closing time: 6 sec
- thumb joint abduction adduction range: 0-120°
- finger joint flexion range: 0-90°.

Each finger is actuated by one DC motor (1727 006C FAULHABER™ with IE2-512 Encoder and 16/7 14:1 Gearbox) located in the forearm which pulls a cable through a linear slider connected to the motor through a leadscrew (Fig. 5).

The artificial hand is equipped with nine Hall Effect position sensors (one for each finger joint), four incremental encoders (one for each motor), two three-component force sensors (one at the thumb and the other at the index fingertip) (Fig. 6) and eight Hall Effect switches (two on each slider and two on the thumb ab/adduction mechanism) for the encoder calibration.

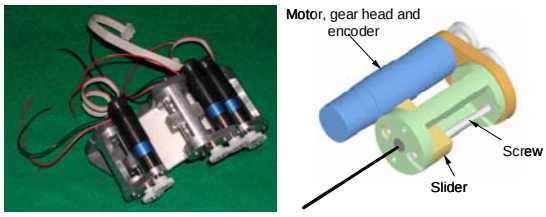

Fig. 5 The actuators carrier of the humanoid robotic arm and 3D CAD model of the single actuation and transmission system of each finger.

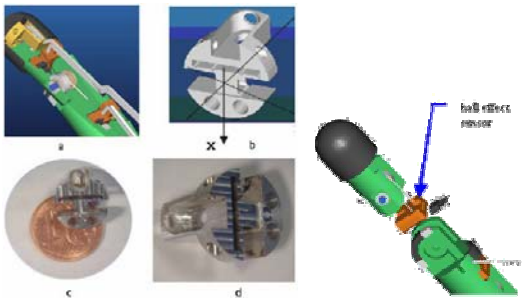

Fig. 6 The three-component force sensor and the Hall Effect joint position sensor.

C. *3D CAD Model and Dynamic Analysis*

The 3D CAD model of the artificial hand was built by using ProEngineer™ (Fig. 7). Clearance and interference problems were virtually analyzed through a dedicated feature of this software tool.

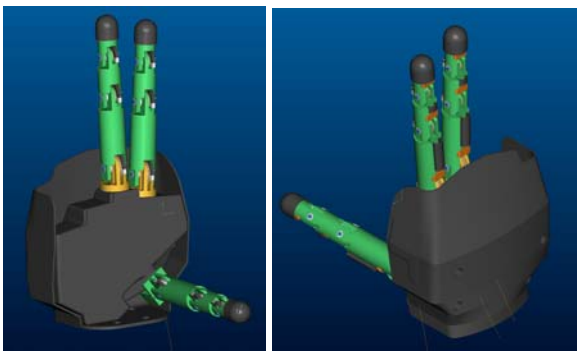

Fig. 7 The 3D CAD model of the artificial hand.

The kinematics and dynamics of the artificial hand during free closing movement towards the object has been simulated using ADAMS™. This software is a multibody analysis simulation program that solves the rigid body dynamic equilibrium equations and that directly interfaces with ProEngineer™. The optimum values of the design parameters (pulley radius and spring constants) were determined by building the virtual prototype and analyzing it through these simulation tools. The sensory system and the mechanical structure were designed and verified by means of FEM simulations implemented on ANSYS™.

III. THE CONTROL SYSTEM

The control is aimed at exploiting the main properties of underactuation (i.e. the self-adaptation and the reduced number of active degrees of freedom) to perform grasping tasks in a way comparable to the human case. Basically, in this initial phase of the work only one finger is taken into account (Fig. 8) and its behavior is controlled and analyzed while closing to grasp a cylindrical object.

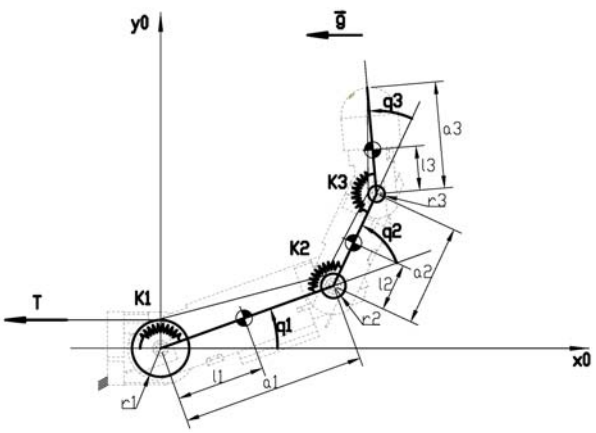

Fig. 8 Finger scheme.

As shown in Fig. 5, the actuation system for each three-phalanx finger is based on one DC motor moving a slider mechanism which transmits motion to the phalanges. In particular, the three joints corresponding to the three phalanges are coupled in terms of kinematics and dynamics.

Kinematic coupling among the joints is related to the slider kinematics by the following relation:

$$\begin{aligned} x_{slitta} &= r_1(q_1 - q_{10}) + r_2(q_2 - q_{20}) + r_3(q_3 - q_{30}) \\ \ddot{x}_{slitta} &= r_1\ddot{q}_1 + r_2\ddot{q}_2 + r_3\ddot{q}_3 \end{aligned} \qquad (1)$$

where:

- q_1, q_2, q_3 and $\ddot{q}_1, \ddot{q}_2, \ddot{q}_3$ are the joint angles and accelerations, respectively;
- r_1, r_2, r_3 are the pulley rays;
- x_{slitta} and $\ddot{x}_{slitta}$ are the slider displacement from the static equilibrium configuration and acceleration, respectively;
- q_{10}, q_{20}, q_{30} are the initial equilibrium joint angles.

The dynamic relation among the joints is expressed in terms of joint torques τ_1, τ_2, τ_3 and cable tension T as:

$$\begin{aligned} \tau_1 &= r_1 T \\ \tau_2 &= r_2 T \\ \tau_3 &= r_3 T \end{aligned} \qquad (2)$$

In view of Eqs. (1) and (2) it is conceivable to try to control the artificial hand in the joint space or else in the slider space, as formulated in the following. Joint space stands for the space where the joint variables of position, velocity and acceleration are defined; on the other hand, the slider space is that where the slider variables of position, velocity and acceleration are defined.

A. PD control in the joint space with elastic compensation

Dynamic relation (2) is used to actively control the first joint (i.e. q_1) and passively move joints q_2 and q_3. The proposed control law is a modified version of the standard PD control in the joint space with gravity compensation [18] and is expressed as:

$$\tau = K_P \tilde{q} - K_D \dot{q} + g(q) + \tau_e \qquad (3)$$

where $g(q)$ is the estimation of the joint gravitational torque and K_P and K_D are the diagonal gain matrices for the proportional and derivative control actions, respectively. With respect to the standard PD control plus gravity compensation, an elastic term is introduced (i.e. τ_e), in order to compensate for the preloaded springs located at each joint (Fig. 8).

The joint elastic torque is expressed as:

$$\tau_e = K_e(q - q_0)$$

being K_e the diagonal matrix of the spring elastic coefficients and q_0 the vector of the equilibrium joint angles.

In the specific case of a single three-phalanx finger, Eq. (3) is referred only to the first joint and K_P, K_D and K_e are positive scalars.

B. PD control in the slider space with elastic compensation

Control in the slider space exploits (1) to move joints q_1, q_2, q_3 by directly controlling the slider motion. Hence, the same PD control with elastic compensation as for the joint case is formulated for the slider case. The resulting control law is:

$$T_S = K_{PS}\tilde{x}_S - K_{DS}\dot{x}_S + g_S(q) + T_{e_S} \qquad (4)$$

where

- $K_{PS}\tilde{x}_S$ and $K_{PS}\dot{x}_S$ are the proportional and derivative actions on the slider position and velocity, respectively;
- $g_S(q)$ is the effect of the gravitational torque at the level of slider;
- T_{e_S} is the elastic contribution of the preloaded springs.

Mechanical relations allow moving from the joint space to the slider space and vice versa.

IV. SIMULATION TESTS

Simulation tests have been carried out in order to achieve the following goals:

Goal 1. to validate the two proposed control laws and compare their performance;

Goal 2. to compare the behavior of the biomechatronic hand with the human hand.

To this purpose, the authors have selected one specific task, i.e. grasping a cylindrical object, studied data extracted from humans during grasp and made the artificial hand perform the same task.

Tests have been carried out in a simulated environment developed in Matlab/Simulink under the assumption of index finger closing in a 2D space in absence of gravity.

From the literature it emerges that the tip trajectory that best fit data recorded on the human index finger during grasp is the logarithmic spiral [11, 12]. In polar coordinates (r,θ) it can be expressed as:

$$r = A\left(\exp\left(\theta \frac{\cos b}{\sin b}\right)\right)$$
$$A = 1.3394\left(l_d + l_m + l_p\right) - 23.255$$
$$b = 1.633 \qquad (5)$$

being l_d, l_m and l_p the link lengths in the human case.

Moving to Cartesian coordinates, the motion of the human finger is described in terms of joint variables θ_1, θ_2, θ_3 as:

$$x = l_p \sin\theta_1 + l_m \sin(\theta_1 + \theta_2) + l_d \sin(\theta_1 + \theta_2 + \theta_3)$$
$$y = l_p \cos\theta_1 + l_m \cos(\theta_1 + \theta_2) + l_d \cos(\theta_1 + \theta_2 + \theta_3) \qquad (6)$$

where relation $\theta_3 = 0.7\theta_2$ seems to hold [11, 12]. From here, inverse kinematics allows extracting joint trajectories corresponding to the tip logarithmic spiral. In particular, condition $\theta_3 = 0.7\theta_2$ on the joints is used to solve redundancy in the plane. Simulation results are reported in Fig. 9.

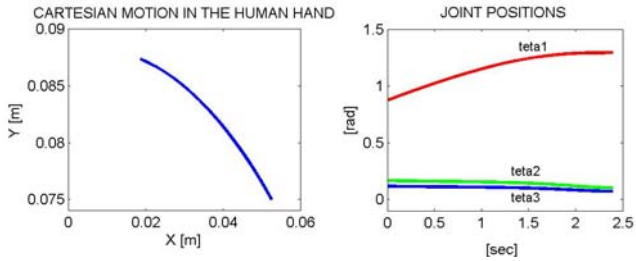

Fig.9 Tip motion in the Cartesian space (a) and corresponding joint trajectories (b).

In order to address goals 1. and 2., the dynamics of the index finger of the artificial hand has been simulated in the plane and control laws (3) and (4) have been tested during a closing operation. The reference trajectories for both controllers have been extracted from the human case by means of the inverse kinematics (for the control in the joint space) and Eq. (1) (for the control in the slider space).

Figures 10a and 10b report the joint positions and the joint error in norm for the case of PD control with elastic compensation in the joint space. Instead, Figs. 11a and 11b show joint positions and slider position error in norm in the case of control in the slider space.

From simulation results, the PD control with elastic compensation in the slider space seems to better control the finger motion. In particular, with respect to the control in the joint space, it reduces joint oscillations around the mean value, due to the springs at the joints (Figs. 10a and 11a); then, the norm error is very small and rapidly converges to zero (Figs. 10b and 11b).

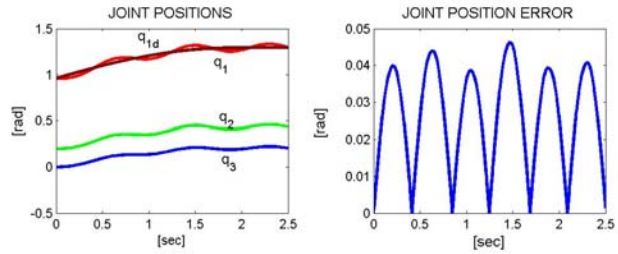

Fig. 10. Joint positions (a) and joint error in norm (b) for the control in the joint space.

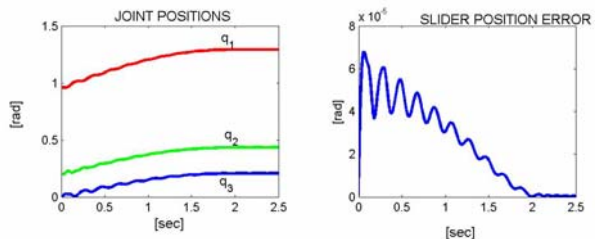

Fig. 11 Joint positions (a) and slider error in norm (b) for the control in the slider space.

Further, the Cartesian behavior is reported in Figs. 12a and 12b in terms of index finger tip motion and is compared with the human case (Fig. 9a). In view of the coupling in the artificial hand dynamics and kinematics, it may be observed that the tip trajectory is quite far from the human trajectory, particularly as regards the control in the joint space, where only the first joint trajectory is needed as reference.

However, the integrated approach between mechanics and control and the CAD tools will allow modifying design parameters of the artificial hand in order to replicate as better as possible the reference model (i.e. the human behavior), by exploiting control results.

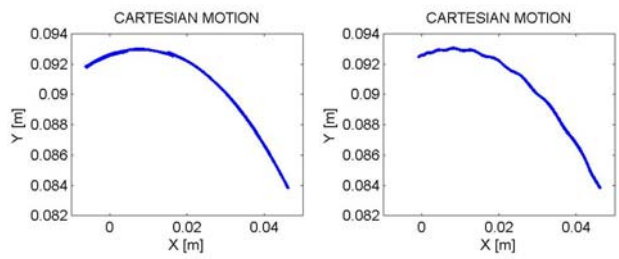

Fig. 12 Tip motion in the Cartesian space for the PD control in the joint space (a) and the PD control in the slider space (b).

V. CONCLUSIONS

This paper has presented a biomechatronic approach to the design of an anthropomorphic artificial hand, trying to combine requirements coming from the bio-inspiration with requirements coming from the application fields, i.e. prosthetics and biomedical robotics.

Motivations and basic features of the proposed mechanical design have been reported in the first part of the paper. In particular, the concept of finger underactuation has been explained and the actuation system and the sensory system of each finger has been described.

The presentation of the control system has been detailed, with emphasis on the mathematical formulation of two simple PD control laws adapted to the hand mechanics.

Simulation tests have been carried out in order to compare the two control systems and evaluate the behavior of the artificial hand in a common task of grasping a cylindrical object. Comparison with data extracted from humans has been finally reported.

Future work will be addressed to optimise the design of the artificial hand by using simulation results and the comparison with the human case, in order to improve the adherence to the human model and to envisage the required adaptations needed for different possible applications, e.g. hand prosthetics, robotic end effectors, etc.

ACKNOWLEDGMENT

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