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Artificial upper limb development, simulation and control

F. Casolo, M. Camposaragna & M. Molaschi
Politecnico di Milano, Italy.

Abstract

The artificial upper limbs are widespread in the amputees community and have two distinct aims: to restore the aesthetic or the mechanical function of the limb. Functional prostheses can be passive - with friction joints - or active. The last ones can be classified as "body-powered" or "externally-powered". The "externally powered" are currently supplied by electrical actuators and driven by EMG signals: if the active joints are more than one they are driven sequentially and the system includes a selector. Over a certain number of active axes this approach is stressing and produces very unnatural movements. This is one of the reasons why, at present, shoulder joints are only passive. An innovative active shoulder with two d.o.f. based on a differential gear is presented. It is a component of our total artificial limb (4 or 5 d.o.f.) for which a new approach to the driving system has been studied. In this case it is asked to the patient only to try to drive the hand in the space independently by the other joints. Discarding the sequential approach, the relative motion of head and trunk is chosen as command signal for the preliminary driving tests and a virtual reality system have been built to evaluate the driving algorithms. The head-trunk relative motion is measured by an instrumented spatial linkage. The results of two algorithms has been analyzed and compared. Future development will concern a miniaturized device for collecting kinematics data, the improvement of the command algorithms and some feedback for the prosthetic limb

1 Introduction

1.1 Mechanically functional and cosmetic prostheses

The artificial upper limbs are widespread in the amputees community and have two distinct aims: to restore the aesthetic or the mechanical function of the limb.

Both aspects are very important. The cosmetic prostheses, which have only aesthetic functions, are very common and have ever been produced since the evolution of wood and leather handcraft. At present, the main reasons for using their modern version are: the low cost, the durability, the light weight, the simplicity and the natural look. The low cost and the simple technology required to manufacture some basic models, made their diffusion possible also in not developed countries. A small number of patients like these limbs better because they want to avoid any chance of physical or mental stress related to the use of the functional prostheses.

Some primitive functional upper limb prostheses have been produced, as well, some century ago: the limbs used by hand amputee horsemen to handle the lance are, for instance, interesting examples from the middle age.

The are many kind of functional prostheses for the upper limb and many way to classify them. Primarily they can be grouped into passive or active. The first ones need external actions to modify the joints angles or to link a working tool to the end-effector. To this group belongs the functional limb of above example, to whose hand a sidearm can be fixed. Most of the current passive functional prostheses for the upper limb can keep a stable position because they are equipped with friction joints (fig.1) and can be displaced by applying an external torque; the latter action can be produced by means of the opposite –active– arm, or by pushing the prosthesis on an external structure.

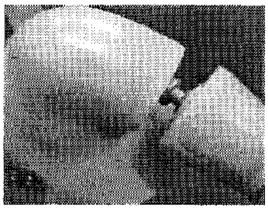

Fig.1 Passive shoulder friction joint (3d.o.f.)

1.1.2 Active prostheses

The wide range of typologies of arms belonging to this class is justified by the different level of amputation, the different age, the motivation and the physical condition of the patients. The active joints can be classified as "body-powered" or "externally-powered". The artificial arms for high level amputation presently in use, may include active body powered, active externally powered and passive joints, all in the same limb.

1.1.2.1 Body-powered systems

The body-powered systems move the artificial joints by means of forces generated directly by the residual muscles –as it is achieved by means of "cineplasty"[1]– or indirectly, through the movement of other body segments, or taking advantage of the prosthesis inertia. The cineplastic surgery create some external links to the muscles where the artificial joint's operating cables (or bars) are connected. This interesting technique has been fairly popular in Europe and in USA in the middle of last century. Some patients are still satisfied by prosthetic devices obtained with this surgery. But, due to retirement of the members of the specialized surgical teams working at the end of the World War II and to the evolution of the externally powered prostheses –capable to exert higher forces–, the cineplasty gradually faded out of use –in USA in the early 70s and in Europe in the late 80s–. Nevertheless, this method, recently reintroduced, seems to be a promising approach to drive, but not to power, sophisticated hands with many active axes.

A system still very popular to power and drive artificial arms, is based on harness and transmission cables connecting the prosthetic joint to a movable segment of the body. The main limits of this solution are the difficulties to power multiple axes, to exert high forces and to obtain adequate excursions.

Cable systems are also used to drive the looking mechanisms of the joints in the so-called "kinematic prostheses". These prostheses are driven and powered by the movement of the residual part of limb and exploit the inertia characteristics of the prosthetic segment. Both the last two body powered systems often originates quite unnatural motion paths.

1.1.2.2 Externally-powered systems

At present, the only external energy currently supplied to the artificial limbs is electrical, is stored in rechargeable batteries and, except for few hydraulic joints, also the actuators are electric (e.g. dc motors).

The great majority of electro-mechanical hands currently in use have only a single degree of freedom. They are generally driven by means of the electromyographic (EMG) signals.

Artificial upper limbs with two or more active axes cannot be driven directly by coupling two EMG signals to each motorized axis because, normal subjects are, in general not able to manage simultaneously more than two EMG signals. If the active axes are two or three (e.g. hand, wrist and elbow joints), the motion control is usually sequential: the system includes a mechanism – activated by a cable or by another EMG signal – to switch the command from a joint to the next. This technique is inadequate for an higher number of active axes because it originates very unnatural arm movements and requires a long series of actions. This problem significantly increases when also the prosthetic shoulder is motor driven. A special case of externally powered system concerns prostheses where the electrical motors are controlled by a physiological sensory feed back from the muscles or other tissue of the cineplasty. In this case, the feeling of the patient is to move the hand by means of his muscles but on the contrary the forces are exerted by the electrical motors. This newly developed technique is promising but require a surgical treatment and is suited to a restricted number of patients.

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2 Development of new artificial arms including active shoulders

2.1 Rationale of the project

The statistics on below shoulders amputees show [5] that many of them would like to add active degrees of freedom to their artificial limb in order to better perform some everyday actions. This can be extrapolated to the patients disarticulated at the gleno-humeral joint because their greater lack of physiological movements is very evident.

No motorized shoulder are commercially available yet. The scarce industrial interest is probably related to complexity of the system, to the rather little number of shoulder amputees with respect to the hand amputees, and also to the exiguous requests by the clinicians. Obviously the clinicians will start to prescribe a motor driven shoulder only when it can be proven that the prosthesis fulfills the requirement, can be easily driven by the patient and do not increases his mental stress . At present, the only interesting prototype of artificial active shoulder presented by the literature is designed at Edinburgh University and has a single active axis.

Because of this lack of devices where the patient request is present, our research group at Politecnico di Milano in cooperation with Centro Protesi Inail (BO) is developing a new artificial arm equipped with a multi-axis active shoulder.

2.2 A critical subject: the choice of the driving approach

As above stated, current approaches are inadequate for driving artificial limbs with four active axes plus the hand ones; as a matter of facts, selecting and driving all these axes, one at time, is not acceptable for many obvious reasons. On the other hand, not even to the healthy subjects, the upper limb physiological motion tasks requires to consciously manage the kinematics of all the joints of the chain; but it only need to focus on end-effector. Therefore, in order to try to replicate the natural behavior, our approach is based on the prerequisite that the patient must try to move directly the the hand and not all the active joints. This target involves two very different problems. The first and certainly the most difficult, concerns the design of a hardware and software system for decoding the desires of the amputee to move the artificial hand within its working area. The second concerns the computation of the driving signals required by the motors in order to place the hand where it is required.

The problem of supplying to the system information on the desired position and orientation of the hand in the space can be solved in many ways, none of which is ideal. One interesting approach may be the use of pectoral cineplasty with a concept similar to the EEP of but in this case the muscle excursions are not connected to the control of any specific joint but only of the end-effector. This technique requires to identify some terminals suited to connect the driving cables and a surgical intervention is needed. Similar kind of information, could theoretically, be extracted from the electromyographic signal of the same muscles, but the practical test, up to know, are not encouraging.

Another not invasive method consist of using little movements of other body segments to identify the hand desired position. This approach lead us to develop, test and optimize the technique without any surgical intervention and using for the tests both amputees and healthy subjects. We selected the head-trunk relative motion as a possible driving signal for the limb displacement and demonstrated that by means of little movements of the head it is possible to perform most of the every day upper limb tasks.

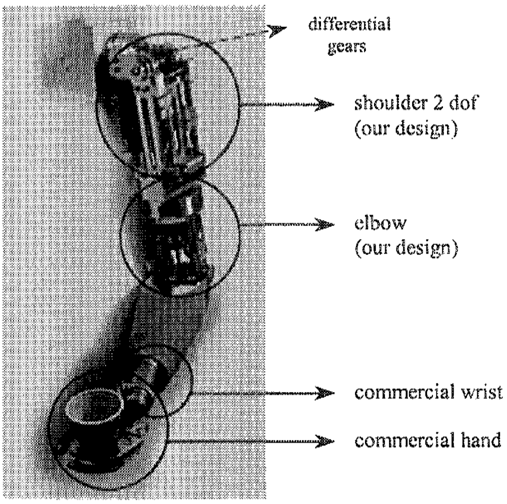

Fig.2 The artificial limb first prototype

2.3 Arm prototype and a measuring device

The arm designed, simulated and built (fig.2) has 4 active d.o.f., plus one of the hand. While a new one with 5 d.o.f. has been, up to now, only designed and simulated.

Both are characterized by an innovative shoulder (2 d.o.f.), based on a differential gear moved by two electric motors through a flexible transmission. The elbow of the first prototype has also been designed by our group - and is currently used by few above elbow amputees -. It is based on a bar linkage, which, including only revolute pairs, reduces the energy loss for friction and guarantee good efficiency and low noise.

The system architecture allows to impose the desired hand position in the space and partially to control the hand orientation. In order to guarantee an adequate hand working space -including the mouth for eating and drinking - the absolute orientation of the first axis of the differential gearing and the relative orientation of the elbow axis with respect to the arm, have been optimized. The optimized working volume of the hand is displayed in Fig.3a, where the colors highlight the orientation of the grasping axis nearest to the vertical. It's possible to note that

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the grasping axis orientation allows to drink or to eat with a spoon only within a small portion of frontal workspace.

To avoid the need of a refined optimization of the geometrical parameters, to increase the hand useful working volume and to improve the hand orientation control, a new elbow joint with two active axes has been designed (for the new arm). This elbow replicates the shoulder mechanism but it is smaller. With this choice, the natural d.o.f. of shoulder around the arm longitudinal axis, sacrificed in the shoulder prosthesis, is replaced at the elbow level. The simulations show that the workspace of the new arm, with 5 active axes(fig.3b) is wider and allows to adjust the hand orientation, in order to keep the grasping axis direction rather constant, within an extended volume.

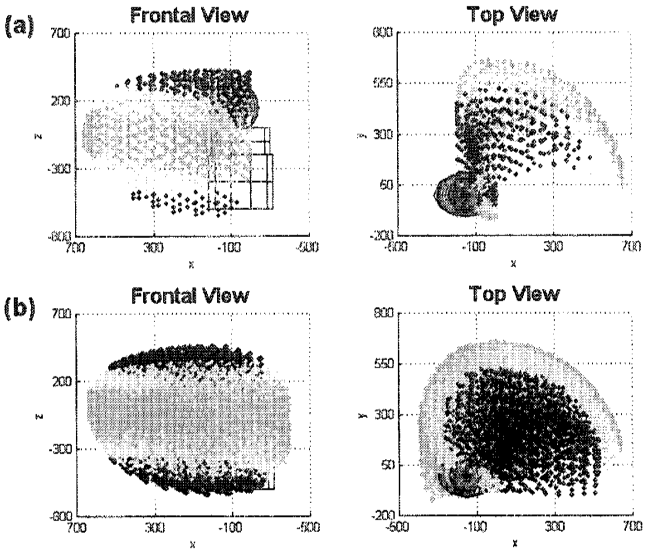

Fig.3 a: 4d.o.f. arm; b: 5d.o.f. new arm. Working volume of the two prosthesis: the colors show grasping axis orientation nearest to the vertical (potential glass position)

In order to choose the optimal algorithms linking the head-trunk relative motion to the hand movement, a 6 d.o.f. instrumented linkage has been optimized and built. The measuring gauge is connected to an hat and to a soft frame to be placed on the subject back (fig.4).

3. The preliminary driving algorithms

The linkage above described is only planned as a research and development tool: not all the kinematics parameters collected by this equipment must be used in the final driving algorithms. Our objective is to try to optimize some driving algorithms, in order to require, as input, only few kinematics parameters easily collectable by a miniaturized device that will equip the commercial upper limb system. For testing and optimizing the driving algorithms, a virtual reality system has been developed (in language C++ using directX 8.0). It allows the patients to practice with the algorithms by moving a virtual arm matching with the real prosthesis. One interesting advantage of the simulation approach is that the new prototypes can be preliminary evaluated even before their production.

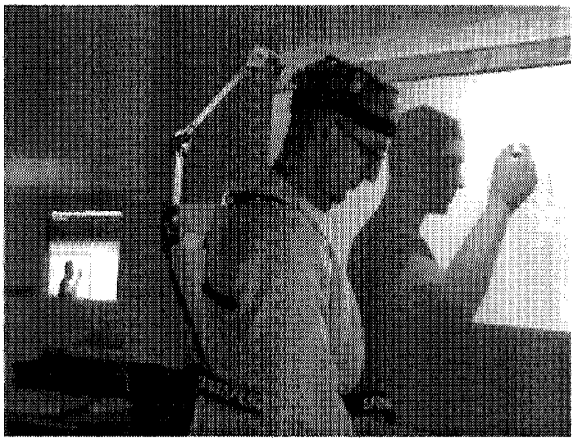

Fig.4: A subject with the measuring linkage in front of a maxi screen used for the visual feed back of the virtual artificial arm moved by means of the head (the point of view of the arm can be freely chosen)

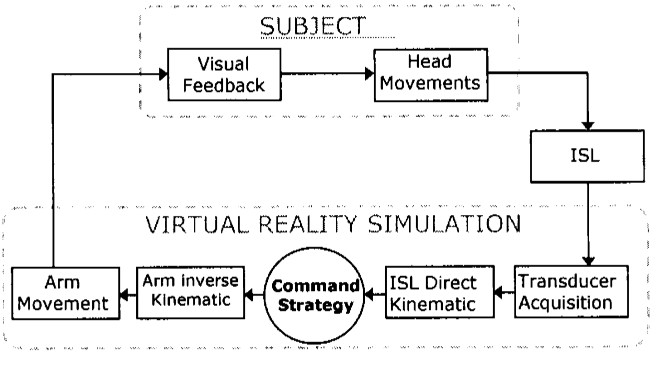

Fig.5 : Schema of the virtual reality system loop

Up to now, the two most effective algorithms tested on normal subjects are the so-called "pursuing" and "proportional" methods. The first links the hand target to a vector perpendicular to the face frontal plane, with the origin between the eyes; the distance of the target from the origin will be referred as "depth coordinate"

The second produces the target displacement by means of small head angular movements on the horizontal (fig.6) and on the sagittal planes at the same time.

In both algorithms, the depth movement is driven by the head anterior/posterior translation; for this we discriminate only three states: forward, backward or no motion, which lead to target displacement further or nearer to the body, at constant velocity or its stop(fig.7). Optionally, the same three conditions are realized by means of another mechanical device not involving the head, namely two push buttons to be placed in the prosthesis, and currently acted by hand.

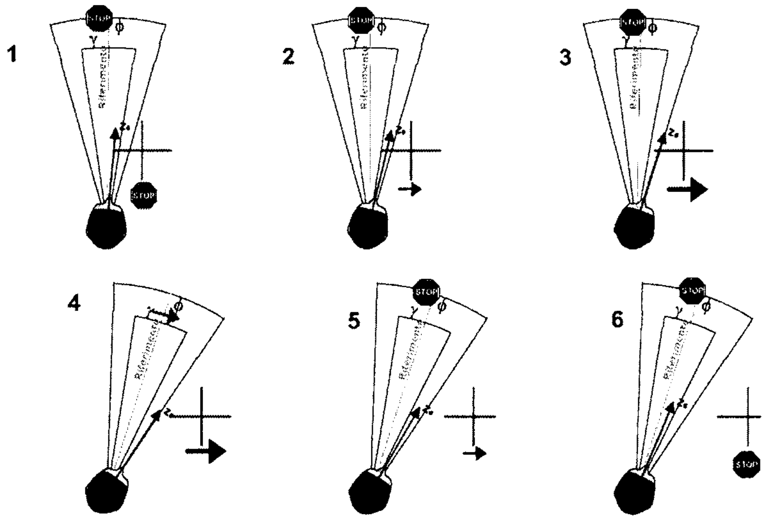

Fig. 6:Working schema of the "proportional algorithm" with a moving reference frame: 1) when head axis z is within the angle ϕ, the target (+) doesn't move; 2-3) when z is outside γ but inside ϕ, the target moves with growing velocity as described in the lower graph of this figure; 4) outside γ, the target velocity doesn't change and all the reference system moves together with z axis; 5) newly within angle γ, the target begins to slow down, and 6) stops when it's again within ϕ

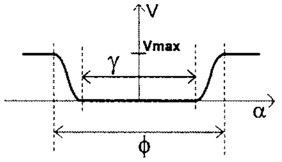

Fig.7: velocity diagram versus ϕ and γ

After the location of the hand target by means of the above algorithms, the hand must be moved toward the target. The target is only an attractor for the hand: the system automatically takes into account the kinematics constraints of the limb. These constraints and the dynamic limits of the motors are also implemented in the simulation software designed to train the patients for using the prosthetic limb.

In order to obtain a fluid and rapid movements we choose to link the velocity to the hand distance from the target with of an exponential negative law, which allows to maintain the maximal velocity for most of the trajectory and to approach smoothly the target.

4. Some results from the tests

Some extensive tests on healthy subjects have been recorded by the simulation system [3] and processed: the exercises require to perform some actions with the virtual artificial arm, driving it by means of the head.

The subjects must drive, for instance, the virtual arm to grasp, in a precise order, some objects lying in the virtual 3d space displayed on a maxi-screen. (Fig.8). The results (Fig.9) allow us to draw some preliminary remarks: training is very helpful for all the subject tested; the pursuing method is more intuitive and effective for the task carried out and to drive the hand in the "depth" direction by means of the head motion is more difficult than using the mechanical switch.

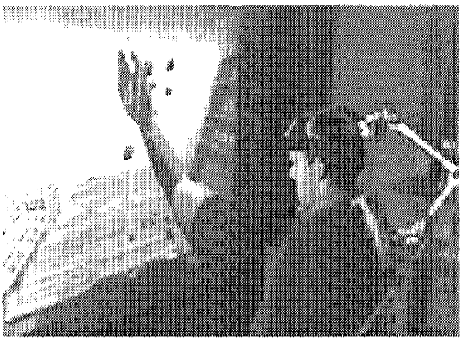

Fig.8: A subject during an exercise: with his virtual hand, he must pick, as fast as possible, all the boxes on the screen following a prescribed order

More details about the third remark can be deduced from fig.10. The quite flat normal distribution functions of the data obtained by using the head for the depth command remark the difficulties of the subjects to execute similar movements in different trials. On the other end, driving the depth component of the 3D motion with a mechanical switch (push buttons) increases the precision and the repeatability of the whole movement.

Moreover, even if the algorithm of the proportional method seems less effective it has not been discarded, but on the contrary it will be optimized. Some patients, in fact, affirmed a preference for it because it require a less emphasized head motion and consequently their movements looks more natural.

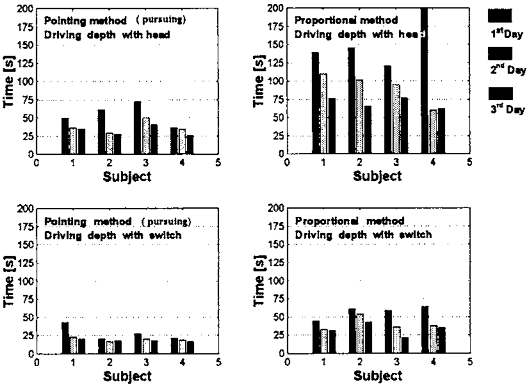

Fig.9: Mean time (on 14 trials) required to complete a test with the developed algorithms. Four subjects results grouped by days are shown

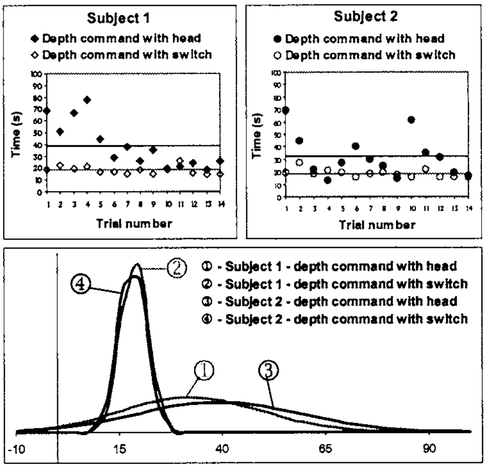

Fig.10: The first two graphs display the results of 14 tests for each subject, performed with the two different ways to drive the depth. The third graph shows the normal distribution function of the above data.

5. Artificial limb feed-back is still an open question

All the externally powered arms, driven by mean of the displacements of another body part or by using EMG signals, have only the visual feed-back and a limited force feed-back at the prosthesis interface with the body. Future development of our virtual reality system will reproduce the force feed-back by means of an haptic interface connected to the shoulder when a total upper limb prosthesis is simulated or to the arm when the limb is disarticulated at the elbow level.

However this feed-back is too poor for the total artificial limb externally powered, whether real or simulated: there is no redundant information that may help to speed up the movements, and there are not enough data to drive the limb with the dark. Thus it is very important find a way to implement at least a position feed-back to the artificial limb.

Unfortunately many electrical or mechanical feed-back procedure acting on the skin at the prosthetic interface seems to be useless because the patient become accustomed to the signal. Some researchers suggest that this question may be solved increasing the interaction of surgeon an engineers to refine some surgical procedures like cineplasty, and to create new human-prosthesis interfaces.

6. Concluding remarks

The increase of the active degrees of freedom of the prosthetic upper limbs can help to improve the quality of the life of the amputees, only if it do not increases the physical or mental stress of the subjects.

The lack of externally powered total upper limbs is certainly related to the difficulties of setting up an adequate driving system. Nevertheless the electromechanical design of a prosthesis fulfilling all the request considered essential for the patient satisfaction are also very challenging.

The total upper limb prototype designed and built by our research group satisfies most of the project requirements and the hand can perform correctly most of the basic physiological actions of the everyday life.

The virtual reality system built for this application can help the medical team to evaluate the patient attitude to drive an artificial upper limb prosthesis, to customize the driving algorithms and to train the subject. It is also used to run preliminary tests on prosthetic arms before their construction.

This research prove that it is possible to perform some tasks with a prosthetic hand, real or virtual, focusing only to the hand motion, and commanding it only by means of little movements of the head. The two algorithms already implemented (pursuing and proportional) are only a first attempt to solve the problem: many other may be selected and optimized on subject characteristics.

The results show that the method based on the "pursuing" algorithm is more intuitive and effective for the tasks carried out during the tests and that the dept perception is probably poor during the simulation. It is also noticeable that the ability of the subjects rapidly increases with training.

One important target of the virtual tests is to find the algorithms requiring the minimum number of kinematics parameters to drive the hand. It is in indeed essential to design a miniaturized data collecting device to equip the prosthetic limb.

One open question that require in future the maximum effort is the study of the proper feed back of the prosthetic armThe increase of the active degrees of freedom of the prosthetic upper limbs can help to improve the quality of the life of the amputees, only if it do not increases the physical or mental stress of the subjects.

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