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CIRA

CENTRO ITALIANO RICERCHE AEROSPAZIALI

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ABSTRACT

The widespread use of composite materials in advanced industries (like the helicopter one) is still limited by high manufacturing costs due to process complexity, which sometimes leads to "hand made" products and to high waste amount.

Manufacturing process automation can reduce the composites total cost, by reducing manpower and waste amount, and moreover may increase the final product quality. The above considerations are especially true for "filament winding" techniques. It is not easy (and sometimes it is impossible) to wind complex shape structure elements such as forks, straps, by means of "traditional" filament winding machines. Difficulties arise especially when more than one rotation axis is requested, so that sometimes these complicated pieces are, by far, hand made. This "manual" winding points out that a solution may be found in the use of an anthropomorphic manipulator, eventually co-operating with external positioners. The application of these "robotic cells" in other manufacturing fields (gluing, arc welding, manipulating, etc.) is well appreciated for the flexible adapting to complex processes and for their relatively low plant costs (due to robots large scale producing). Their use has to deal with the task programming complexity, the performing accuracy and the tool design.

In this work a winding robotic cell is considered. The number of degrees of freedom is redundant with respect to the minimum needed to achieve the main task, that is the correct positioning of the end-effector with respect to the piece being wound. The degrees of freedom not strictly requested for this task can be exploited in order to optimise joint configurations with respect to secondary tasks, such as hard limits, collisions avoiding and process quality improving.

An off-line path-programming environment has been developed. It takes into account the co-operation between the anthropomorphic arm and the additional axes, aimed at redundancy exploiting for the trajectories optimisation and the part program generation.

The simulation environment has been used to verify the feasibility of a blade-hub fork link manufacturing for a generic helicopter.

Keywords : composite material, filament winding, robot, kinematic inversion

1 FILAMENT WINDING

Filament Winding (F.W.) is a well-known composite manufacturing process. It allows lying down on a deposition support a continuous fibre filament coming out from a suitable delivery system, till the complete (or partial) body coverage and the wanted thickness are reached. The deposition tool draws a trajectory taking into account the body shape and the way to align or to cross the circuits of fibres during the process.

Automated filament winding by means of computer controlled machines is the "natural" evolution of manual techniques, where human operators lay down the fibres on the deposition support.
Manual techniques can be thought for any kind of shape but are not suggested when a good quality and repeatability are required. Manufacturing quality, in fact, is strictly related to some process factors such as winding tensioning control, correct fibre winding, production time, repeatability. Human operators cannot easily control all these factors, while in the last decades, automated winding plants have demonstrated to be well suited to achieve high level of quality.

This is actually true just for simple axisymmetric shapes, for which the technology can be considered "mature" [1]. For more complex shapes (even not axisymmetric), process quality improvements are still expected from new automated and not traditional plants, aimed at substituting manual techniques, which are still fundamental [1][2].

PROCESS MAIN FEATURES

Table 1 summarises the main steps in the traditional manufacturing process design. In this case already existent plants are supposed to be used, so that the principal design effort is devoted to the path generation.

F.W. path design process		
ANALYSIS OF REQUIREMENTS	OPTIMISATION	WINDABILITY
Applied loads *Structure and geometry*	*Path design solving* *FEM analysis*	*Part program generation*

Table 1

The first step is the structural and geometrical requirement analysis of the part to be manufactured and of the applied loads.
Since the elements (fibres) which will make the structure are themselves non-isotropic and their mechanical properties are direction dependent, it follows that the winding path (that is, how the fibres are being placed) affects the structural properties. The master way is to try to place the fibres so that their highest strength would be exploited as well as possible within the stress/strain field.

Optimised winding factors (that is, ply-angles, ply-number etc.) can be iteratively found in order to best satisfy structural criteria, overcoming all specific path design problems.
Structural aspects are explored by means of usual FEM software packages.

Moreover the designed path has to be checked in terms of hardware constraints on windability (i.e. collisions, tensioning, etc) and of limits imposed by machine configurations.
The commonly used filament winding machines, having few degrees of freedom, allow to best perform helical or hoop coverage on to suitable rotating mandrels, so that for traditional pieces (usually axisymmetric shapes, vessels, tubes etc) "windability", i.e. winding hardware feasibility, is not an heavy and crucial design target.

PATH DESIGN SOLVING

The technology complexity calls for an integrated off-line simulation environment. All the following factors are crucial items found in almost every process involving filament winding technology [3].

Deposition support

The fibres need a physical support to be wound on, i.e. a mandrel. Such a support may be removable or not: in the former case it is removed after curing of the composite material, in the latter it also has a structural or a containment function and remains finally integrated in the manufactured piece.

Alignment and closing domes

The fibres need to be aligned on the mandrel with a suitable path in a continuous way. This task also requires the help of edge extensions having the function of closing domes. The winding goes on to the closing domes in order to allow the correct fitting of the circuits to be wound and to prepare the alignment for the reverse course. Such domes, indeed, have to be at most modified if are part of the structure itself (like for closed end vessels). Otherwise, they have to be ad hoc designed and then applied to the structure. In this last case the closing domes will be cut and removed after curing.

Slippage tendency

The fibre paths on the mandrel are not all equally "allowable". The naturally stable paths are minimum length and minimum potential energy curves, i.e. geodesics. But geodesic lines impose strong constraints on windable shapes. Whenever the friction between fibres and surface (or fibres and fibres) is high enough, it is even possible to wind along non-geodesic trajectories, with no slippage, allowing a larger class of structures to be wound. The "slippage tendency" parameter is a measure of how much fibres would try to slip away from non-geodesic trajectories.

Fibre bridging

When winding on to a surface with reverse curvature, the fibre could fail the right profile due to its tension, missing the rest on the surface. This is known as fibre bridging.

ARIANNA

"Arianna" is a simulation software tool developed at CIRA to analyse and overcome these typical FW problems and to generate a correct input for FEM analysis. "Arianna" is strongly oriented to the overall process integrated simulation [4].
Main features are briefly the following:

- ☐ simulation and analysis of the winding paths;
- ☐ automatic generation of FEM model for structural analysis of the part;
- ☐ generation and analysis of the winding machine axes motion (with reference to collisions and motion dynamic features);
- ☐ generation of the part program suitable to pilot the numerical controlled machine.

2 WINDING ROBOTIC CELLS

Even if for traditional parts and plants the experience and knowledge is well assessed, automated design and manufacturing of complex shapes is still a challenge [1].

Helicopter industry is an application field interested in this innovation, since some composite structural elements are still hand made. In this case the attention is pointed out essentially on the pieces quality and process flexibility, oriented at small batches more than massive production [5]. In this context the interest is growing towards a robotic solution that, from a conceptual point of view, is very attractive, not only for a mere intuitive substitution of an "anthropomorphic" hand made process.

EXPECTED ADVANTAGES

The application of "robotic cells" in other manufacturing fields is well appreciated for their flexible adapting to very complex processes in their different phases. Tasks like gluing, arc welding, laser cutting, for example, call for a specific attitude to complex movements and tooling. In all these cases complex and optimised trajectory profiles have to be generated for the main task achievement, for which it is common to have more than six degrees of freedom.
The whole production process is planned, with different actions, before, while and after the main task is achieved: optimal positioning of pieces, tools changing for different processes, part transferring and fixing, etc.
Moreover, the possibility to easily change the part to be produced has to be considered. Multiple small batches of parts can be planned and re-programmed saving costs and time. Programming capabilities and specific dedicated software CAM packages for these purposes are the basis of "flexibility" concept.
Not only production costs can be reduced. The widespread use of robots and their large series production has obviously lowered plant investment costs. Filament winding machines are usually manufactured in a very low number of specific samples, rating on each one a large amount of development cost. These development costs would be even higher if machines with great number of axes were conceived by means of a dedicated design. Some of the machinery development problems, i.e. those related to the movement, can be solved by adopting a well suited general purpose hardware, that is a standard off-the-shelf robot cell, instead of dedicated winding equipment [2]. In this way the major effort can be paid in the tool development and in the planning software, to improve process quality and flexibility.

In the last decade, two main examples have been proposed, respectively at the Center for Composite Material (CMC), University of Delaware [7], and Production and Automation Department (PMA), University of Leuven [6]. In the former case a thermoplastic composite placement device has been developed and integrated in a robotic cell. In the latter a tape winding robotic cell has been used to wind a T-piece, by means of a specially developed tool.

DRAWBACKS

Robots have, however, some specific disadvantages that only partially can be recovered by sophisticated planning software and tool design. Accuracy and synchronisation are probably the most critical ones, especially when a robot is used in co-operation with external positioner axes [6].
The last generation of industrial robotic cells has been improved so that it is common to find controllers able to interpolate and synchronise robot and external axes up to 16 independent motors. On the other side, accuracy, especially in the trajectory-tracking task, is still a design challenge for robotic control community [8]. Even if more and more improvements have been reached, Cartesian gantries of filament winding dedicated plants are usually more precise than articulated robot kinematic chains.

These peculiar aspects have to be joined to the major path complexity (due to complex shapes !) and to all other difficulties above described for traditional F.W.

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3 OFF-LINE PATH-PROGRAMMING ENVIRONMENT

An answer to all the problems above described could be found, again, by means of an integrated off line simulation environment.
The CAE instruments described above are used for automated filament winding processes on traditional standard Cartesian geometry and few degrees of freedom machines. The main aim in that case is the optimised path design to achieve structural requirements.

In the robotic case the windability hardware constraints become the crucial factor. The same instruments could be naturally extended to more complex kinematic chains, adding the chance to interactively optimise a set of configuration parameters. By means of such a tool, the designer can explore and observe all different aspects of the overall process, from the fibre path and structural characterisation to the plant configuration and to the actual winding realisation and performances.

This simple idea is very attractive and represents a guideline for the composite manufacturer community [7][9][6]. But it is still difficult to find off-the-shelf general-purpose software, which practically realises it. Even if several packages for specific applications, fibre path planner and robotic cell simulator, already exist separately, it is rare to find an overall integrated environment aimed both at basic cell configuration and optimal path design.

CIRA RESEARCH AND DEVELOPMENT ACTIVITIES

CIRA Process Technology Department is co-ordinating a multidisciplinary research activity developed in this particular field. The main purposes are:

- ☐ design and realisation of an off-line simulation environment for a generic robotic winding cell;
- ☐ design and realisation of an experimental set-up;
- ☐ design and realisation of special tools for different deposition techniques (dry and wet fibre winding, fibre placement even for thermoplastic prepreg).

Based on CIRA previous assessed experience on path generation and structural validation, the "windability " aspects (crucial for robotic multi-axes solutions) have been now more deeply studied. Recent advances on kinematic inversion techniques for redundant co-operative robots have been investigated aiming at integrating the overall design methodology.
R & D activities aimed at software and hardware requirements definition for the above objectives can be summarised as follows:

1. Design and Operation Procedure selection
2. Procedure test and Algorithms preliminary implementation

1. DESIGN AND OPERATION PROCEDURE SELECTION

A preliminary theoretical feasibility analysis phase has been already successfully concluded.
The process main features have been analysed and mathematically formulated, focusing on the design parameters to be optimised.
A trade off evaluation of possible optimisation algorithms and strategies has been performed. This analysis has finally led to the selection of design and operation procedures, parameters, variables and indexes needed for a highly automated optimisation process. Obviously not all choices have been automated, but a direct designer role has been foreseen, based on his experience and on an intensive use of simulation environment.

2. PROCEDURE TEST AND ALGORITHMS PRELIMINAR IMPLEMENTATION

The above procedures have been tested by means of a first implementation of the selected algorithms.
In order to achieve a rapid and effective concept validation, the attention has been pointed out at basic mathematical results. In this case, a Matlab/Simulink environment has been used for this, due to its flexibility and availability, leading to an "essential " software with the only drawback is a relatively poor CAD graphic interface.

DESIGN AND OPERATION

The design and operation procedure selected in the robotic case is a natural extension of the above F.W. process (Table 1). The following table represents final block formulation of the overall design.

Robotic F.W. overall design process				
ANALYSIS OF REQUIREMENTS *Applied loads* *Structure and geometry*	OPTIMISATION *Path design* *solving* *FEM analysis*	WINDABILITY		
		1. CELL CONFIGURATION	**2. OPTIMAL JOINT TRAJECTORY**	**3. PART PROGRAM GENERATION**

Table 2

Structural and geometrical requirements lead to the fibre deposition path design such as described for traditional F.W. Moreover it should be noticed that for robotic winding applications the fibre slippage could be reduced compared to traditional F.W., and even avoided, thanks to the use of grooved supports and/or rests properly applied on them.

The output of the path design fixes a knot sequence *Pi* and suitable interpolation criteria to represent a curve *P(s)* on the mandrel, with *s* length abscissa. On this curve a natural triedron can be defined, which determines *R(s)*, where R is a rotation matrix.

On the other hand, windability plays a primary role in the robotic technology.

WINDABILITY

1. CELL CONFIGURATION

Cell configuration data refer to the geometry of all mechanical parts of the plant, that is the cell with its arms, positioner, rotating axes, the moving mandrel and fibre feeding systems.

The optimisation of these parameters is based on a trial and error iterative simulation process guided by the designer. In the early set-up design phase to evaluate the impact of different "basic" choices such as arms typology and positioning, axes number, workspace definition, tool dimensioning is required. These parameters, in fact, are not easily modifiable once a set-up is fixed. It is clear that some other parameters "piece dependent", like mandrel positioning on rotating axes, may be updated.

2. OPTIMAL JOINT TRAJECTORY

Once the deposition path and the cell configuration are given, the n joint co-ordinates q have to be determined so that the desired winding of the defined path could be performed. For this, the deposition eye has to move according to precise requirements for position and orientation. These requirements are strictly related to the corresponding P (position) and $\boldsymbol{R}$ (rotation matrix) of the desired path. This is the main target.

The optimisation involves a set of decision variables (q variables + free fibre length l), with their constraints, which could be redundant with respect to the main target. Redundancy allows secondary targets to be defined and followed. This can improve the process quality measurable by suitable indexes. The operator can select targets and, based on index evaluation, may iteratively change them. Eventually he may also decide to change configuration parameters, going back to the 1 block (cell configuration).

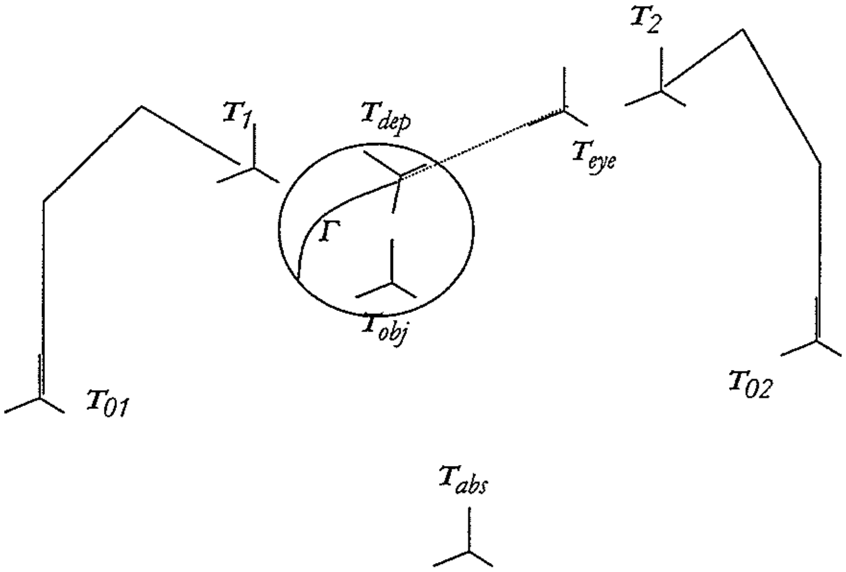
As last step of the optimisation chain the time axis is assigned in order to achieve the maximum value of acceleration and velocity limits of the joints.

3. PART PROGRAM GENERATION

The $q(t)$ time histories have to be translated in a part program for the cell controller, using its proper language.

REDUNDANT COOPERATIVE ROBOT KINEMATIC INVERSION TECHNIQUES

The general case of two kinematic chains has been considered, one devoted to move a mandrel or a generic shape support, the other one for the deposition eye, with no limits for the number of axes. The redundancy, obtained by the exceeding number of axes, is typical when the plant is not designed and optimised explicitly for one kind of piece, but to have a general-purpose machine. More axes than necessary for a specific task mean more possibilities in terms of realisation of complex pieces, a better dexterity in the movement, a usually higher velocity. But, on the other side, it means also a higher planning complexity, especially for kinematic inversion, and a major care to maintain good realisation accuracy: more axes could mean, in practice, more induced errors.



In the following reference frames are represented by homogeneous 4x4 matrices T. An equivalent minimal representation with a 6 elements variable **x** could be adopted, using for example Euler angles and Cartesian co-ordinates.
Two sets of generic kinematic chain parameters, Dh_1 and Dh_2 have been considered, according to the Denavit Hartemberg representation [8]. For each one, a vector of joints co-ordinate is defined, q_1 and q_2. The relative motion between deposition eye T_{eye} and mandrel T_{obj}, i.e. ${}^{obj}T_{eye}$ [1], has been expressed in terms of both arms direct kinematics, $T_1(q_1, Dh_1)$ and $T_2(q_2, Dh_2)$, represented by the frame of their extreme flange (end-effector), of their relative positioning with respect to an absolute frame T_{abs}, and of tool and mandrel geometry [15]

$${}^{obj}T_{eye} = F(Dh_1, Dh_2, {}^1T_{obj}, {}^2T_{eye}, q_1, q_2)$$

The required deposition path on the object is described by a curve $\Gamma(s)$, with s natural length abscissa. The natural osculating frame (tangent **t**, normal **n**, binormal **b**) associated with it determines a rotation matrix $R(s)$. $\Gamma(s)$ and $R(s)$ combined in an homogeneous representation give a ${}^{obj}T_{dep}(s)$. By means of a particular projection operator P, which takes into account required free fibre length along the tangent

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[1] It means T_{eye} expressed in T_{obj} frame

vector and relative rotation of deposition eye, the reference position and orientation of the deposition tool can be expressed

$$ {}^{obj}\underline{Tref}_{eye} = P({}^{obj}T_{dep}(s)) = {}^{obj}\underline{Tref}_{eye}(s) $$

To reach the imposed alignment target, the equality ${}^{obj}T_{eye} = {}^{obj}\underline{Tref}_{eye}$ has to be guaranteed for each s value,

$$ {}^{obj}\underline{Tref}_{eye} = F(Dh_1, Dh_2, {}^{1}T_{obj}, {}^{2}T_{eye}, q_1, q_2) $$

This kinematic direct formulation has to be inverted, i.e. q_1 and q_2 values have to be found, for each s, taking into account some basic constraints, avoiding collisions of arms, tool and mandrel, and considering end limits for the joints.

The usual way to approach numerically the solution of the functional problem is to discretise the s variable, considering a finite number of knots s_i, to invert only these points, obtaining q_{1i} and q_{2i}, and to interpolate them to have the final solution $q_1(s)$ and $q_2(s)$. Obviously, sampling rate has to be high enough, increasing complexity of the global solution. At each knot **i** a formal minimisation problem is posed:

$$ \min_{q_{1i+1},\, q_{2i+1}} \quad \mathbf{dist}\left({}^{obj}\underline{Tref}_{eye}(s_{i+1}),\, F(Dh_1, Dh_2, {}^{1}T_{obj}, {}^{2}T_{eye}, q_{1i+1}, q_{2i+1}) \right) $$

$$ G(q_{1i+1}, q_{2i+1}) \leq 0 $$

where G is a set of constraints, and **dist** is a function that measures distance between positions and rotation matrices, which is possible using particular $SO(3)$ Lie group properties [10]. The solution passes through a constrained non-linear minimisation solving technique.

The solution search strategies for the above general formulation, already implemented in several available packages [18], can be very complex and articulated.

On the other side, several real time robotic oriented approaches use fundamental results of these numerical techniques to solve the problem [12],[8] of kinematic inversion in a suitable low computational and formally interesting way. They add to general methods all possible data and available information coming from peculiar aspects of robot kinematics. This class of methods is known as CLIK (Closed Loop Inverse Kinematic) [8][13].

In the simplest form, referred to a single robot, a "follower" dynamic system is designed which continuously adjusts its output q to reduce the difference between reference and effective tool motion, while s is increasing with time t [18]. The basic idea is the inversion of differential kinematics that locally linearises velocity expression for the end-effector of a robot. In fact, differentiating the direct kinematic expression in the minimal form, a locally linear relation is obtained :

$$ x = k(q) \qquad\qquad x' = J(q)\, q' $$

where x represents position and orientation of end-effector in minimal representation, $J(q)$ is jacobian matrix of single robot kinematic function $k(q)$.

The follower system finds for each t value the best direction, i.e. derivatives q', to move the joints variables. A closed loop expression for the general inverse solution which guarantees that drift error can be recovered continuously with an acceptable dynamical behaviour [8] is given by integrating the following:

$$ q' = J^{\dagger}(x'_d + Ke) + Pq_o' $$

where $J^{\dagger}$ is Moore Penrose pseudo-inversion of jacobian, K is a gain matrix, while P is a null space projector $(I-J^{\dagger}J)$, e is the current error between x, as function of q, and x_d which is a reference, q_0' is an arbitrary joint velocities vector. The first term, $J^{\dagger}x'_d$, is a minimal norm solution based on common pseudo-inversion. It is eventually increased by the J null space contribution, Pq_0'. Joints velocity vectors in this null subspace do not produce any Cartesian motion, so that they do not perturb the main task, satisfied by the minimal norm solution. Possibly they can generate internal motions, the end-effector is not involved, aimed at reaching secondary tasks.
A secondary task (in a priority scale) can be formulated exactly in the same way, by means of a follower system. It generates velocity contributions q_0' to satisfy the specific secondary task, but only filtered components Pq_0' of them are added to the minimal norm solution of the first task. The method can be iterated for a generic *i-th* level task in an efficient multitask formulation with a priority task strategy [14][17]. For each task it is necessary to calculate task jacobian and its Moore-Penrose pseudoinversion, with the relative null space projector.
Some suggestions about the possibility to avoid the singularity problem have been adopted [17]. Singularities arise when the rank of jacobian decreases, i.e. some singular values reach zero. In this case pseudo inversion can fail without adequate damping methods [8].
Besides, in the multitask problem, "algorithmic artificial singularities" may arise. In this case each considered task, i.e. primary and secondary, has not a singular jacobian, but they both cannot be contemporarily obtained. So a priority strategy can avoid algorithm failing, preferring the primary task achievement [14].

Adapting the above single robot solution to a co-operative motion involving two robots, q has to collect $q1$ and $q2$, J has to be the jacobian of eye kinematic function with respect to the object frame and can be evaluated starting from geometrical jacobians of two arms [15].

The velocity reference x'_d can be evaluated assigning a priori an abscissa time law *s(t)*, which could be eventually a posteriori scaled to maximise the joints accelerations and velocities. Alternative forms referring also to acceleration references have been proposed and tested [16]. The knowledge of these references anticipates as possible a feedforward action to increase real time precision and to improve the tracking capability of the follower.

A simpler off line version of this real time oriented approach has been proposed and tested. The discretised knots generate constant reference values for the follower system, which integrates the recovered error on a virtual time axis and stops only if convergence criteria and tolerances are satisfied. In this way the sequence of values q_i is generated at fixed s_i, while all intermediate virtual values that are evaluated can be analysed to observe convergence properties and to set better gain parameters.

The number of achievable secondary tasks depends on redundant degrees of freedom. Several task definitions have been adopted and verified, aimed at collision avoidance and process quality improvement. Collision avoidance calls for a maximisation task of minimum distance between all elements that can collide. Process quality can be measured by means of "manipulability ellipsoids" based indexes [11]. In this way those motion directions that limit the effects of force disturbances and numerical imprecision can be detected.

4 TEST CASE: BLADE-HUB FORK LINK

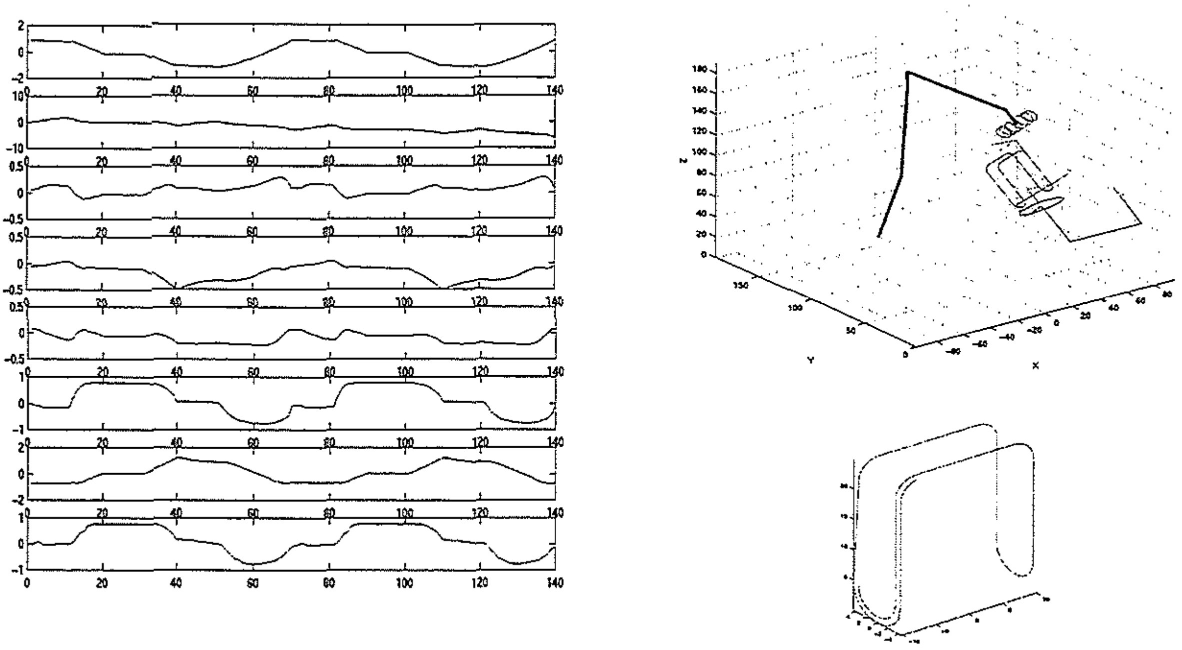
Several tests have been selected and performed to evaluate the above procedures and algorithms first implementation. The interesting case here proposed is a blade-hub fork link, for which a kinematic feasibility study has been applied.

PATH GENERATION

Structural and geometrical requirements were considered in a previous work performed at CIRA [5]. A specific support geometry and a deposition path on it were designed.

CELL CONFIGURATION

Several parameters have been finally fixed by means of iterative simulations.
An anthropomorphic arm with six degrees of freedom has been finally chosen, co-operating with a two axes orbital positioner, for a total of 8 moving axes. The effects of unlimited rotations for the 6th robot axis and for one of two positioner axes have been considered.
A deposition tool has been thought based on analogous experiences. It has been supposed to deliver the fibre directly from a moving and tensioned bobbin, which is transported together with the deposition eye. Dimensions of such a tool have been varied to check the impact on kinematic cell behaviour. The relative positioning of all elements has been also considered, both for distances and orientation.

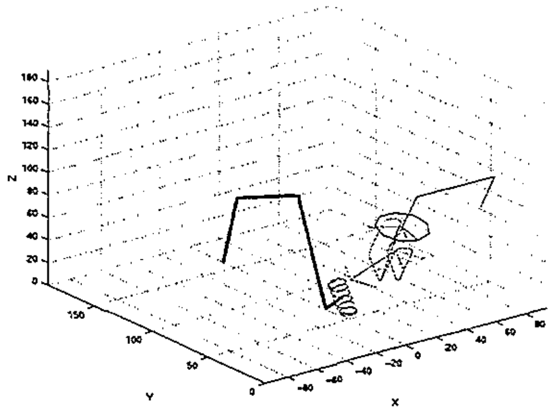


The above figure shows (upper right) a scheme of the anthropomorphic robot, the deposition tool and fibre bobbin, the fork positioned on the fixing system of the orbital positioner. On the left an overview panel summarises the inverted trajectories corresponding to a single circuit of the fork path (lower right).

OPTIMAL JOINT TRAJECTORY

Starting from the fixed deposition path different strategies have been tested to fix a reference for deposition eye. A first approach let the free fibre length l variable in a limited range so that the set of decision variables q_i is increased by this parameter. Some difficulties result here in the appropriate secondary task definition and balancing. Two opposite trends are evidenced by simulation. Moving from a light to a heavy free fibre length control, simulation results pass from a very large robot workspace spanning, to the need of a tensioner with a great rewinding performance. These considerations have finally suggested to keep variable the free fibre length in order to have the deposition eye constrained to move on a spherical surface that includes, with a margin, the fork. In this way eye collisions and unwanted fibre rewinds are implicitly avoided.

The importance of secondary tasks can be immediately appreciated comparing results of simulations with and without "collision avoidance task". The minimum norm solution of the primary task alone may lead to collision and crash of robot arm and positioner (as shown in the following figure). Adequate secondary tasks easily recover this undesirable event.



The selected configuration for the set-up has shown good results in terms of manipulability indexes. The reasons for this can be found in the good compromise between number of axes, workspace dimensions and primary task requirement.

5 CONCLUSIONS

Within fibre deposition technology, industrial robots could be used to wind complex shapes, such as some helicopters structural elements.
CIRA is developing research activities aimed at this new target for automated filament winding, and has already planned to install a general-purpose industrial robotic cell to acquire experimental feedback.
The attention has been focused on developing an integrated off-line simulation environment in order to design either filament wound structures either related robot cell configurations.
Well-assessed experience on path generation and structural validation for traditional F.W. technology were already transferred in the ARIANNA software development. That experience has been now further enriched by means of investigation on the "windability problem", which is crucial for cells with an high number of axes. Recent advances on kinematic inversion techniques for redundant co-operative robots have been exploited.
The cell design and operation procedure has been selected and tested by means of a first algorithms preliminary implementation. The tested core algorithms will be easily C coded just using Matlab automated code generation capabilities. The obtained C code, or its compiled version, will be then ported in a CAD oriented environment. The availability of specific object libraries, such as Parasolid or Acis, makes easier and more practical the development of a sophisticated and impressive Graphical User Interface.
From a theoretical point of view, some improvements are expected by integrating in a unique process both structural and windability optimisation. At the moment these aspects are still separately considered.

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