nonetheless to maintain the inertia moment at the minimum value possible with respect to the pivot axis.

In other words the structure that we are looking for has to be cost effective in terms of useful load - frame mass ratio without compromising the structural stiffness and strength.

Therefore there is a need for a systematic approach for the design process in order to organize work tasks in the best possible way and to solve all of the technical and physical contradictions with the aim of obtaining original, more innovative and more efficient solutions. This has been made possible by using techniques that can support the designer during the concept phase suggesting to him possible improvements, and then supporting him in order to achieve highly efficient constructive solutions from both a structural and a functional point of view. These techniques include:

- Problem solving techniques for the correct formulation of problems in order to achieve innovative conceptual solutions, such as TRIZ [2] [3].
- Topological and Shape Optimization techniques for reaching the most effective shape from many points of view, for example the best rigidity with the minimum mass, etc. [4]

Moreover, thanks to the possibility of obtaining multiple solutions for every single problem, Multi Criteria Decision Analysis tools have been used [5] [6] to help the designer to choose the most suitable one.

All of the selected solutions can be easily and rapidly verified through the use of numerical modeling techniques (from CAD to FEM and Multi-Body Simulation).

2. INNOVATIVE GONDOLA SYSTEM: DESCRIPTION OF THE DESIGN PROCESS

As mentioned in the previous section, the main objectives of the entire project are to obtain a new concept of the “gondola” system, which will be fully adaptable for multi-user loads, easy to transport, easy to assemble, and above all reusable (at least in part). Thus, important improvements are required that cover different points of view:

- **Versatility**: a multi-user load means to have a very wide range of different possible requirements, thanks to different combinations of small, medium and large experiments arranged in the same payload.
- **Modularity**: the realization of structures that can be divided into different, but easy to assemble, modules. A smart modular system is easy to transport and to repair.

Modularity, versatility, as well as an easy way for repairing the gondola (for example, damages after landing), are achieved by means of two types of elements:

- **Replaceable elements**: variables in shape and dimension for arranging different experiment loads.
- **Reusable elements**: generally more complex to machine, these can be considered the “precious part“ of the system. They are reusable for all projects, independently of the size and final shape of the gondola.

As described in a previous work by IFAC-CNR and the University of Florence [1], the whole structure can be divided into two different main structural elements:

1. **The frame of the gondola**: This is the structure in which the experimental load and the solar panels are contained and secured;
2. **The “Spider” structure**: This is the upper part of the gondola, and terminates with an interface for the pivot mount [7].

Since each balloon has a limited lifting capacity, it is simple to deduce that the smaller the mass of the whole structure, the greater the mass of the transportable payload. The frame, which constitutes an important part of the gondola’s mass, must be designed so as to reach the highest strength-mass ratio. The type of frame that has the best structural effectiveness and that is easy to assemble or disassemble is a reticular-type structure with elements that undergo tension-compression stress only. As required for all kind of gondolas, also the geometry of the new concept structure has to be conceived in such a way as to reduce the moment of inertia with respect to the pivot axis, thus minimizing the angular response for any azimuth regulation while preserving all the functional requirements. But whenever the experiment needs to deploy solar panels as well as experimental equipment with particular flight requirements, it could be difficult to overlap the payload’s center of gravity and the pivot axis. For a welded gondola, the problem can be overcome simply by adding extra weight in order to let the two axis overlap each other. The proposed structure uses a regulation system consisting of four arms of a variable length to perform the same operation without increasing the total weight. Starting from the design of the new feature two main problems need to be solved:

- The realization of joints, the behavior of which, should not be too far from a perfectly spherical one;
- The kinematics of the regulation system for the pivot axis.

Unfortunately, the solutions to the above problems trigger a series of secondary problems, such as the sizing of all the elements of the reference structure and the way in which to realize a system capable of recovering the backlash of the joints.

The solution to a series of cross-correlated problems suggests the use of a systematic approach. In any other way it would be very difficult to manage all of the variables on which the main functional parameters depend. Here as follows we describe some cases in which specific tools have been used to solve complex problems.

3. TOOLS USED IN THE SYSTEMATIC APPROACH DESIGN

As mentioned in section one, there are certain important tools that support the designer during the conception phase : the Problem Solving, Topological, and Shape Optimization techniques. Each of these has been successfully utilized to discover the best solution to a set of individual problems.

For each of these, different types of simulations as well as both Multi-Body analysis and Finite Elements Analysis (FEA) software are required in order to verify the validity of the various solutions proposed.

3.1 Multi-Body analysis

Two problems have been faced using Multi-Body analysis:

- The kinetostatics of the joint system located at the gondola base
- The kinematics of the balancing system
- In fact, in order to obtain a better approximation for spherical joints, several types of “real” joints have been found during conceptual activities. Each of them has been analyzed from many points of view, such as manufacturability, the machining and complexity of its assembling. Every solution has been tested by means of a Multi-Body and a FEM software in order to verify the validity from kinetostatic and structural point of view.

The Multi-Body code has also been used to find and verify the solution for the movements of the pivot axis that are necessary for the final balancing of the gondola.

An important feature for the new project is that any pivot axis shift must preserve its perpendicularity with the plane of the base. This peculiarity is, in itself, the most important aspect of the new Gondola’s versatility .

Searching and analyzing, for products coming from the “world” of patent data base, which is especially devoted to regulation plane, we found several solutions that are already on the market; however, none of these was very suitable for the pivot interface shift during the balancing phase.

Then, once the most potential useful solution had been detected, a kinematic study was outlined in an attempt to finding the right number and type of degrees of freedom to assign to every joint in the regulation system.

An analysis of the balancing system reports that the actual kinematic configuration is represented by four universal joint connected to the pivot interface and by four other universal joints connected to the base of the structure.

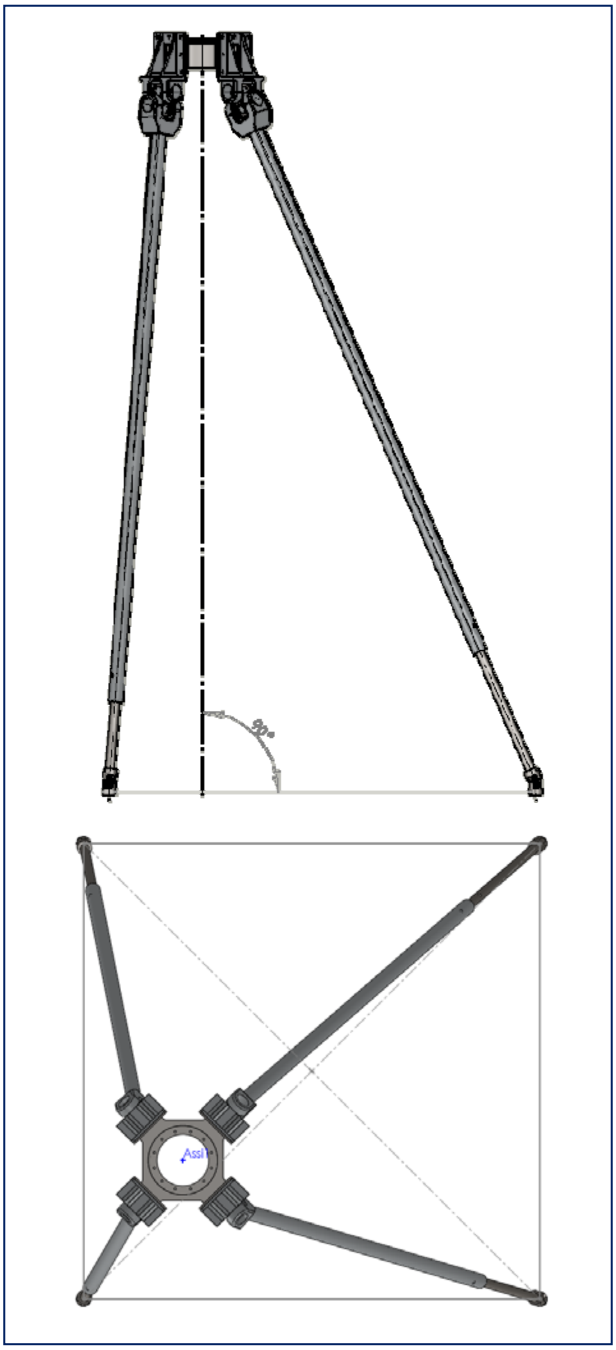

Figure 1. The kinematic condition of the centre of gravity movement that is part of the regulation system

Furthermore the four pairs must be joined by four telescopic bars. With this system every movement of the Pivot is constrained to be a pure translation thus keeping the perpendicularity of the pivot axis unaltered (see fig.1).

3.2 Finite Element Analysis (FEA)

The stiffness and strength specification of each structural element were verified using the Finite Element Method (FEM) from the ANSYS v.12.1 code.

A simplified parametric model has been realized using BEAM elements connected by COMBIN7 joint elements in order to simulate the effects of cylindrical joints, and is connected by MPC184 elements to simulate the behavior of universal joints. By means of this quick-to-solve numerical model, many different conceptual solutions have been verified, the size of the gondola's elements has been determined, and the reaction components have been extracted in order to sustain a more detailed FE model for sizing single parts, such as joints or other critical parts.

In order to take into account the dynamic effects generated by the accelerations to which each mass of the system is subjected, the simulations were performed for two load cases: first, with an applied vertical gravity acceleration value equal to 10G; then, with an acceleration value equal to 5g and with an angle of 45° with respect to the pivot axis. These load cases simulate the parachute opening conditions. By considering the vertical 10g load case, which is the worst condition for the elements of the base of the gondola, an important example can be presented that demonstrates the utility of a simplified FE model. Thanks to this simplified model, in fact, it has been possible to make a rapid check of the conceptual solutions found during the design activity that regard certain coupling options. Starting from a welded joint solution in an attempt to simulate many different configurations and type of couplings, we obtained what can be considered the best solution. Figure 2 show a contour plot of maximum Von Mises stress for a part of a base realized with elements rigidly connected together, while in Figure 3 the same type of plot is shown but for the final version of a base assembled by cylindrical joints.

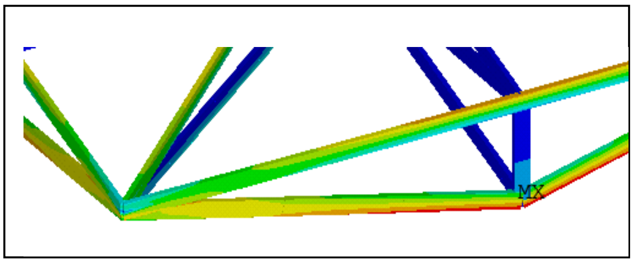

Figure 2. Contour plot of maximum equivalent stress for a welded-joints structure (the red zone indicates a stress level of about 500MPa).

Figure 3 shows how using cylindrical joints to connect elements is the best possible approximation of a perfect form of behavior on the part of spherical joints.

Figure 4 shows the enormous advantage of the solution adopted. In fact, with the same weight of the structure and using cylindrical joints instead of welded ones, a 40% reduction in the maximum stress is realized.

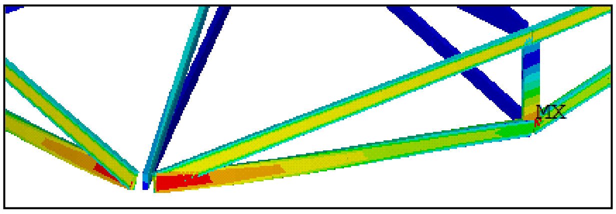

Figure 3. Contour plot of maximum Von Mises equivalent stress for a cylindrical-joints structure (the red zone indicates a stress level of about 300MPa).

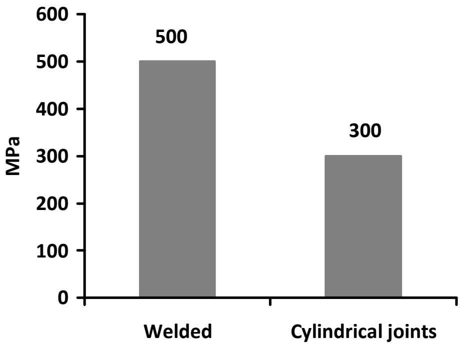

Figure 4. Maximum Von Mises equivalent stress comparison between a welded-joints structure and cylindrical-joints structure, using both the same elements and load configuration.

4. ADAPTABLE GONDOLA SYSTEM: RESULTS

As a result of the entire study, a new concept of the platform was reached, i.e. one that is capable of being transformed in size and shape simply by varying the length of certain replaceable elements while retaining the reusable ones.

The reference structure considered for dimensioning the elements is shown in Figure 5. In this figure it is possible to observe a base consisting of many replaceable elements in the form of aluminum rods with rectangular sections that are mutually connected by means of a series of joints. All the joints of the base connect a honeycomb plane that sustains boxes representing different experiments, and at four corners they connect four telescopic bars by means of four free universal joints. One of the interesting properties of the system achieved is provided by the particular functional characteristic of the two types of joints utilized: central and angular (see figure 6). These joints were designed by considering the possibility of changing the shape of the gondola's base, from square to rectangular.

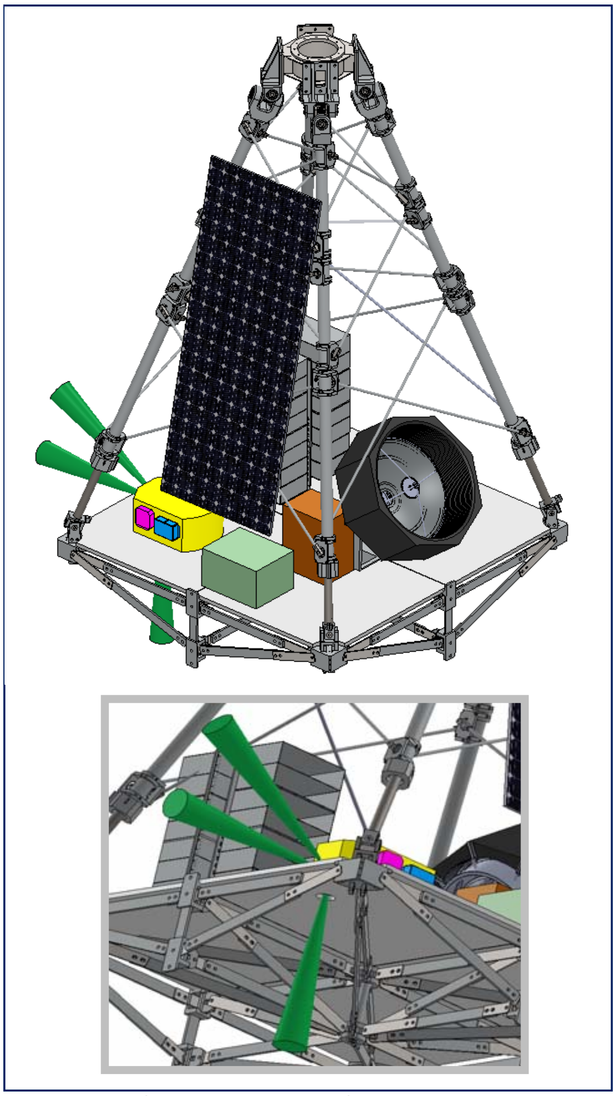

Figure 5. Reference structure of gondola with a possible type of load.

A very interesting result was provided by the possibility of compensating any unbalanced position of the center of gravity (COG) with respect to the pivot axis simply by moving the pivot plane towards the actual COG position of the payload while being in flight–ready condition. This is made possible by the specific kinematic system described in section 3. As previously mentioned, all of the possible movements of the pivot's interface can be performed automatically by respecting the perpendicularity existing between the pivot axis and the plane of the base. With these innovative features, it is then possible to realize many different configurations of the gondola, and also to consider the possibility of adding an extra plane for a better arrangement of the experimental equipment.

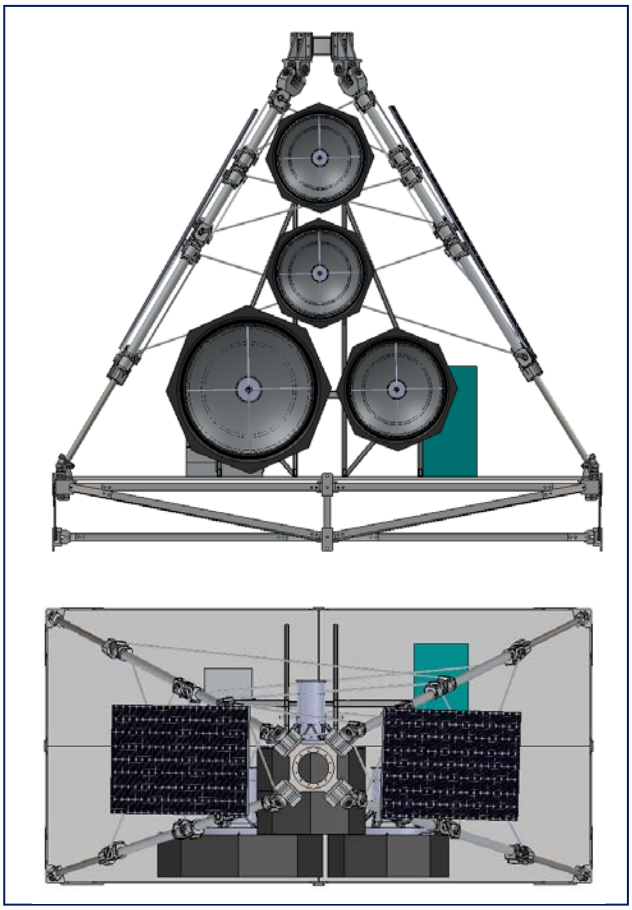

Figure 6. Rectangular-shaped gondola, with a possible configuration of payload.

As previously mentioned, another possibility is offered by the special feature of some joints, by means of which the shape of the base can be changed from square to rectangular, as shown in figure 6.

The reference structure shown in Figure 5 is 4 meters high and has a square base that is 2.5m long on the sides. Moreover, as in [1], it must comply with a vertical 10G acceleration and a 5G acceleration at 45° with respect to the pivot axis. If we consider a total payload mass of 1200 Kg with a 400 Kg ballast mass included (both centered with respect to the center of base of the gondola), an estimate of the structure's mass can be made. The results of the above hypothesis are shown in Table 1. It should be considered that the weight of the new gondola, although lighter than a welded one, is heavier than an hypothetical perfect reticular structure. The increment in the structure mass - and consequent loss of transportable useful mass - is due to the high level of versatility required in this first step of the project. This loss is estimated at around 35 percent, and is closely connected to the mass of reusable versatile joints.

Table 1: Characteristics of the gondola in a reference configuration with 1200kg of useful load

Component	Weight (kg)
Replaceable elements	248
Reusable elements	364
Pivot Interface	48
Total mass	660
Overall dimensions (m)	2.5 X 2.5 X 4

Table 2: A comparison of structural performance between a rigid-welded structure and the new gondola system

Type of gondola	Weight of structure (kg)	Useful load (kg)
Rigid welded [1]	700	760
New Gondola system	660	1200

In defining a performance index Wr as described in Eq.1, it is possible to highlight the considerable improvement given in terms of structural performance.

$$Wr = \frac{Useful\_load}{Weight\_of\_structure} \qquad (1)$$

The welded gondola and the new system have a performance index of 1.08 and 1.82, respectively.

It is essential to emphasize that, as previously shown, this comparison has been made with reference to a square-based gondola measuring 2,5m x 2,5m x 4m; therefore, any variation in terms of dimension or shape implies a variation in the useful load lifted.

Thanks to the smart Parametrical CAD modelling of structures, a very quick visualization of the gondola with experimental equipment mounted is possible. In this way, it will be very easy to find the best configuration for every specific type of load.

5. CONCLUSIONS

A new type of gondola with a high level of component reusability and that is capable of being adapted in size and shape to host many different experiments has been presented. The systematic design process used to attain these results has been briefly introduced, together with some tools for explaining how some important results have been achieved, as well as their validity. A comparison in terms of structural efficiency between the proposed solution and a still widely-used rigid welded one has been expounded. Some different possible configurations of the newly-conceived gondola have also been introduced.

Parametrical CAD and FEM models of the structure have been realized, in order to test many different configurations of possible payloads. This is an important result, because the principal aim of this work was to obtain a system, to be adopted by every consortium, which is aimed at reducing campaign costs, at least from the point of view of both structural design and simplification in the construction phase. Thanks to this new way of building gondolas, it will be possible to organize stratospheric flights simply by receiving the geometrical dimensions and mass of the various experiment from the different research teams by means of the WEB.

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