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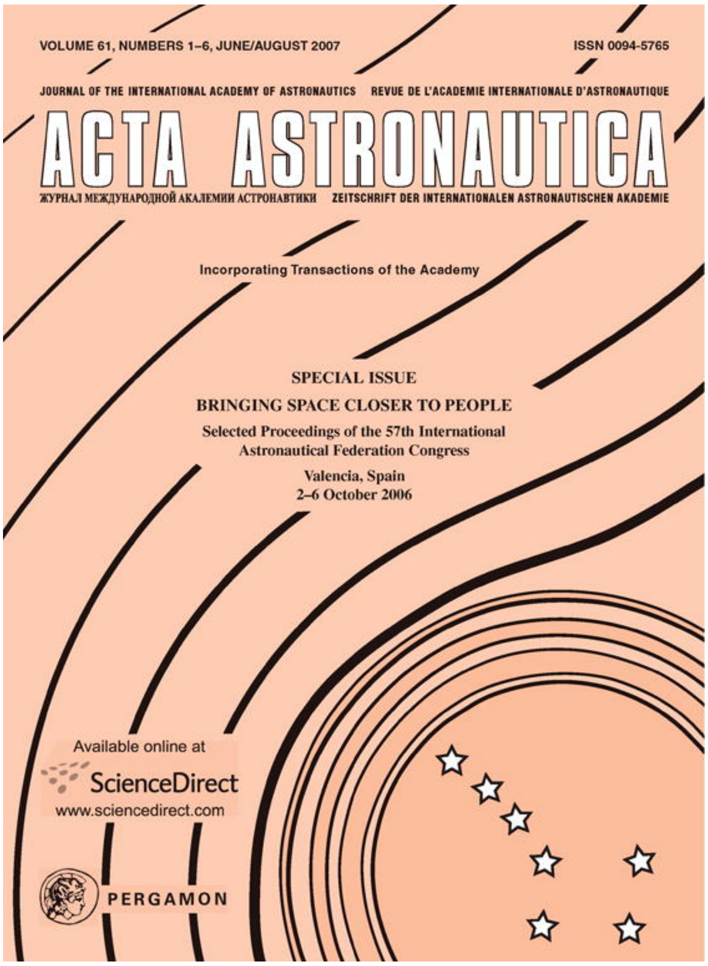
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Deployable structures for a human lunar base

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Abstract

The study Lunar exploration architecture—deployable structures for a lunar base was performed within the Alcatel Alenia Space "Lunar Exploration Architecture" study for the European Space Agency. The purpose of the study was to investigate bionic concepts applicable to deployable structures and to interpret the findings for possible implementation concepts. The study aimed at finding innovative solutions for deployment possibilities. Translating folding/unfolding principles from nature, candidate geometries were developed and researched using models, drawings and visualisations. The use of materials, joints between structural elements and construction details were investigated for these conceptual approaches. Reference scenarios were used to identify the technical and environmental conditions, which served as design drivers. Mechanical issues and the investigation of deployment processes narrowed the selection down to six chosen concepts. Their applicability was evaluated at a conceptual stage in relation to the timescale of the mission.

Keywords: Biomimetics; Space architecture; Deployable structure

1. Introduction

In late 2005 Alcatel Alenia Space awarded a contract to the Institute for Architecture and Design—HB 2 at the University of Technology Vienna to explore the possibilities for deployable structures derived from bionic concepts within the Lunar Exploration Architecture study.

The purpose of this project was to investigate bionic concepts applicable to deployable structures and to interpret the findings for possible implementation concepts for a human lunar base.

Where human experience is limited, role models from nature can deliver solutions exceeding the imagination of technicians and engineers. For the successful transfer of natural principles into technical application some difficulties have to be overcome. One reason for failing to translate nature's concepts into terrestrial applications is the scaling problem. As most bionic role models are smaller than technical (architectural) interpretations, the deadweight is limiting the resizing. Therefore a partial gravity environment as the Moon is advantageous for the application of those concepts. In this study, we concentrated our efforts onto "folding/unfolding" techniques.

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The department of design and building construction has been active in the research of biomimetics and space design for the past six years, developing interdisciplinary design programs. The experience of these students' projects and the collection of candidate bionic role models served as a base for the study.

2. Approach

The approach and methodology applied within the study can be organized as follows:

- Identification of the relevant bionic role-models.
- Identification of space applications for Lunar infrastructure or habitats.
- Selection of role models.
- Preliminary Research into
  - (a) the technical and engineering aspects of the possible structures
  - (b) the technology necessary for possible structures
  - (c) the geometry of the structure.
- Selection of the most valuable concepts for exemplary structures.
- Evaluation and selection of candidate geometries.
- Development of architectural working models.
- Mechanical issues and constructive concepts of candidate geometries.

As movement—deployment—was very important to analyze documentary videos of the architectural working models were produced.

The paper describes sections from the above process of the development of spatial exemplary solutions for deployable structures applicable to Lunar Bases.

3. Identification of relevant bionic rolemodels

A collection of role models, incorporating interesting aspects for the given task, was established. Through several working phases with input and feedback of the Centre for Biomimetics specific role models were identified.

Selected role models were Anglerfish, Bat Beech leaf (Fig. 1), Stick Insect, Cactus (Fig. 2), Earwig, Earthworm, Feather, Fern, Flea, Insect wing, Lobster, Locust, Morning glory, Muscle, Ovary explosion, Palm Leaves, Proboscis, Scorpion, Seed pods, Snail shell, Snail, Snake, Spider legs, Spider web, Spine system, Walnut, Giant water lily.

The following step included the establishment of the main criteria relevant for the study mission.

Fig. 1. Beech leaf.

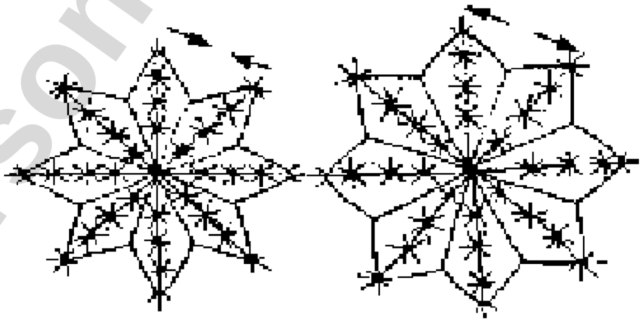

Fig. 2. Symbol Cactus, top view.

The main criteria for the selection of the role models are (but are not limited to):

- Speed regarding deployment process.
- Reversibility as a possible feature.
- Actuation—growth factor, ratio of deployment due to growth, fluid pressure, muscle, $\Delta - t$, Δ-water (osmosis), stored energy.
- Structural performance (mechanical and chemical stabilisation).
- Protection (scale, complexity, etc.).
- Material properties for technical applications (non-hybrid design, functionally graded materials, water content).
- Process properties for technical applications (chemical, drying).
- Complexity.
- Scalability.
- Sensing.

The selected role models were divided into two major categories:

1. Role models being close to a structure forming a volume (Beech leaf, Palm leaf, Cactus, Earwig, Insect wing, Morning glory, Spine system, Giant water lily).
   They got further classified into the following groups:
   - *Fold/deploy*: Plant leaves (Beech leaf, Palm leaf, Victoria Regia), Insect wings, Flower petals (Morning glory), Cactus.
   - *Bellows and folded boxes*.
   - *Rolled up structures*: Proboscis, Fern.
   - *Spines/Backbones*: Tensegrity systems.
2. Role models, which can produce additional features (material, actuation) (Bat, Stick Insect, Earthworm, Feather, Flea, Insect proboscis, Lobster, Locust, Muscle, Ovary explosion, Scorpion, Seedpods, Snail shell, Snail, Snake, Spider legs, Spider web, Walnut, Anglerfish).

For pragmatic reasons and considering the timeframe of the study, further research was concentrated on the first category of role models.

4. Identification of space applications for lunar infrastructure or habitats

The selected role models were set into context of the ESA reference mission for the Moon and requirements regarding the environment as well as the objectives for a lunar base development were developed.

The ESA reference Scenario refers to the "Earth Orbit Rendezvous–Lunar Orbit Rendezvous (EOR–LOR), Exploration Systems Architecture Study (ESAS)":

The two selected reference missions are the Outpost and the Sortie Mission which are briefly described in the following:

Sortie mission: As currently defined, the lunar sortie surface mission objectives are to perform science, demonstrate the transportation system, opportunistic technology demonstration, and opportunistic surface operations demonstration. The Mission duration is 2–4 years, requiring human short time presence without habitat.

Outpost mission: The purpose of the outpost is to establish an initial set of core lunar surface operating capabilities. Additionally, as mission objectives become more challenging and extensive, surface operations will require an evolved set of surface capabilities. The outpost mission requires human presence with 6-month-missions including a permanent habitat.

Internal environment	External environment
- Inertia forces	- Gravity [G]
- Vibrations	- Pressure
- Heat	- Temperature
- Atmosphere	- Radiation
- Pressure Differences	- Impacts
- Mechanical Interactions (Between Occupants and Buildings)	- "Climate" (Latitude)
	- Dust
	- Access To Outside

Fig. 3. Environmental Features affecting the design.

The Table in Fig. 3 describes the main character of the internal (inside a habitat) and external environment.

5. Evaluation of the identified rolemodels for technical applications

The next step in the working process describes the basic requirements for the evaluation of bionic structures, the main objectives for lunar base development as well as selected criteria for the qualitative development relevant for deployable structures on the Moon.

These *Basic Requirement Criteria* will be a basis for the evaluation of bionic models with regard to suitability for the development of mission-capable hardware.

Structural (evaluation) parameters are:

- Strength.
- Stiffness, static and especially dynamic e.g. vibration response.
- Mass.
- Resilience.
- Resistance to corrosion and the other environmental factors.
- Fatigue (see vibratory behavior), if applicable low cycle fatigue and high cycle fatigue.
- Thermal properties.
- Reliability.
- Radiation degradation of integrated electronic parts, if applicable.
- Manufacturability.
- Availability and
- Cost.

Starting from a discussion about the suitable role models for deployment in general, in conjunction with the mission related requirements, reversibility and speed of deployment will become an important topic for the selection. Locomotion as additional topic was excluded from the study content for the time being.

We discerned three deployment types:

1. Non-reversible deployable structures: Deployment is not reversible at all.
   - Habitat and/or associated facilities are packed small for transport.
   - Building purposes include assembly in habitat and/or deployment outside.
   - The landed structure can be reused at a later stage for e.g. shelter, storage, etc.
2. Slow reversible deployable structures: process of deployment takes several hours or days.
   - Possible applications include temporary structures, shelters, roofs, extendable pieces.
   - The landed structure or parts of the structure can be reused for e.g. transport the habitat or parts of it to another location.
   - The lunar base can be expanded for e.g. additional Life Support facilities, shelter, etc.
3. Fast reversible deployable structures: process of deployment takes several seconds to hours.
   - The habitat and/or associated facilities can be transported to a different location on the lunar surface.
   - The lunar base can be expanded for e.g. storage of used structures, etc.
   - Openings, connecting interfaces and moveable parts.

6. Development of architectural working models

Out of the study of the deployment types, indications on structure and volume were derived. In respect to the deployment possibilities, the following three categories were determined.

Each category with their relevant bionic role models was further investigated to derive technical issues for possible candidate geometries.

Folding geometry (*fold/deploy*, *bellows and folded boxes*): This category includes role models that have the potential to create internal usable volume by unfolding. The process of unfolding can be reversible or non-reversible. Role models of this category: Insect wings, Bellows, Plant leaves, Cactus.

The following working models were derived:

- Ladybird I,
- Ladybird II,
- Ladybird III,
- Cactus I,
- Cactus II,
- Cactus III,
- Mussel shell,
- Pineapple folding,
- Folded boxes.

Tensegrity: This category includes role models that are able to create large structures, but no internal usable volume as single element. Interesting role model in this category: Spine.

The following working model was derived: (Deployable) tensegrity structure:

Rolled-up structure: This category includes role models that deploy without creating usable volume as single element. Most of them are reversible. Interesting role models in this category: Insect proposcis, Ferns.

In this category the potential to develop support structures for a human base was identified although these structures deploy without creating usable volume as single element.

7. Developed candidate geometries

The ladybird model is derived from the wing folding principles and the geometry of ladybirds. The wing folding geometry is taken as the starting point and developed further to provide an optimal pattern for the proposed structural system.

Ladybird I (Fig. 4): The basic structure consists of four infolded surfaces. In flat condition the four surfaces describe one flat angular structure. By pulling apart the end parts of the angular structure along one axis the folded "hinge" deploys along an axis perpendicular to it.

+ single translation,
+ little complexity,
− big folded state,
− open structure.

Ladybird II (Fig. 5): The basic ladybird structure is again multiplied 4 times to create a ring. Each ring is rotated by 45° and then added to the first ring along the transverse axis. This is repeated several times to create a self deployable tube.

The tube deploys without rotation by pulling apart its ends.

+ single translation,
+ small initial state,
− large tube volume,
− gaps.

Ladybird IIa (Fig. 6): The ladybird II structure was simplified to create a ring out of rectangular surfaces. This is repeated several times to create a self deployable tube.

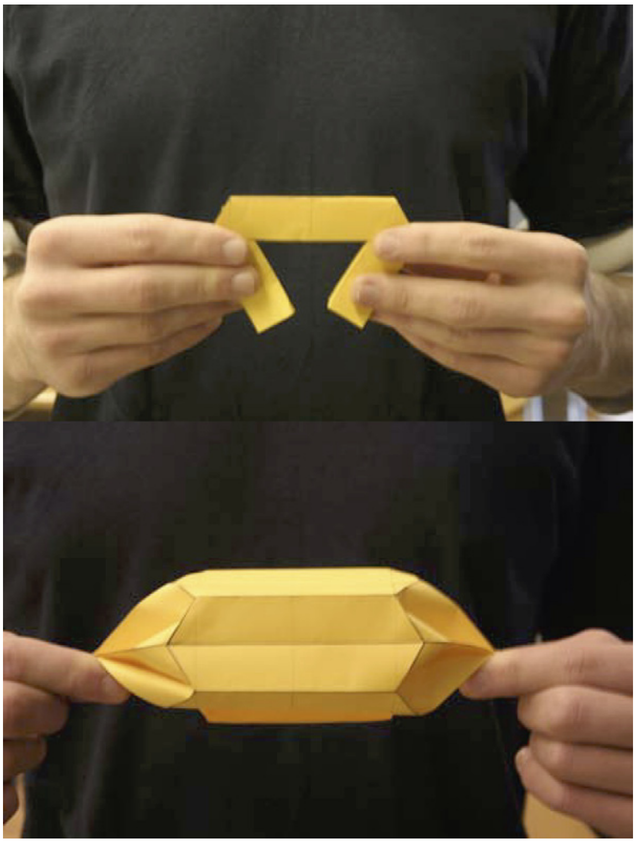

Fig. 4. Ladybird I, paper model.

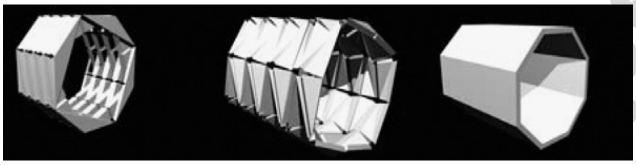

Fig. 5. Ladybird II, computer animation.

The tube deploys without rotation by pulling apart the ends.

Ladybird III (Fig. 7): The first ladybird structure was modified to create different configurations:

The basic unit is multiplied 8 times to create a tube. By rotating the matrix by 45°, adding two of these rotated rings to each other and mirroring them along the transverse axis a tube is created. Discrete actuation could be achieved, by pulling apart the end part.

The growing principle of cactus in horizontal section outlines the deployment pattern of the following candidate models. The inner vertexes of the structure are principally opened up to form the growing (deployed) part.

Cactus I (Fig. 8): Deployment derived from cactus. An even number of planar surfaces is multiplied along their longitudinal edges. In this case eight surfaces

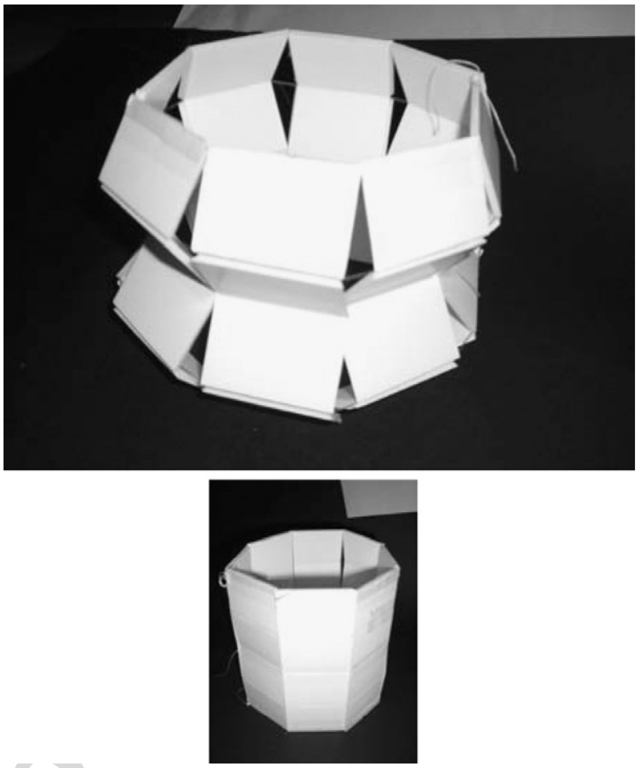

Fig. 6. Ladybird IIa, working model showing deployment process.

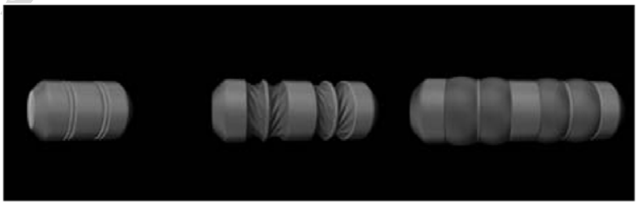

Fig. 7. Ladybird III, computer animation showing deployment process.

Fig. 8. Cactus I, computer animation showing deployment process.

(panels) are multiplied to build a tube. Additional surfaces require a modified folding system. Instead of folding the surfaces to their inside in a star-shape, the folding matrix has to be changed to gain a compact starting package (Fig. 8). The deployment finally generates tubular volume. The hinges between two panels must allow an opening angle of 180° and the control of the movement.

By modifying the measurements and number of the panels' dimensions different sizes of volume can easily be created.

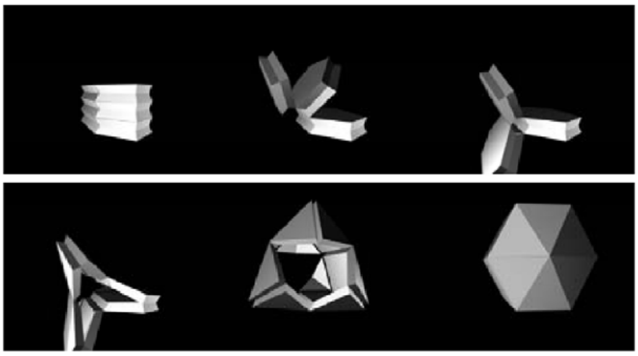

Fig. 9. Cactus II, computer animation showing deployment process.

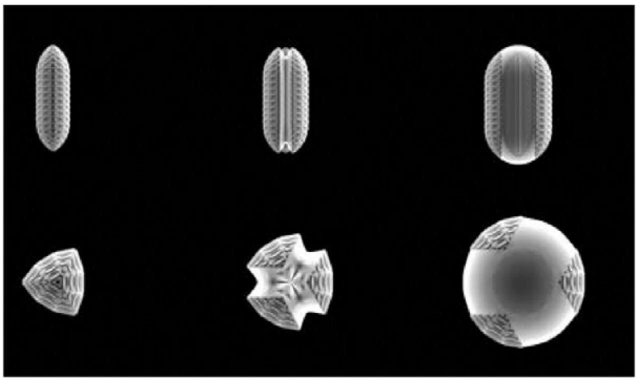

Fig. 10. Cactus III, computer animation showing deployment process.

Two different actuation systems are possible:

- Discrete actuation: by pneumatic structure inside.
- Integral actuation: actuators integrated into the panel system.

Cactus II (Fig. 9): The configuration is a modification of the Cactus I model using a radial deployment to gain a denser package.

Besides, the radial packing this model shows a possible solution for shutting the front faces of Cactus I.

Cactus III (Fig. 10): This further development of the cactus role model is a combination of rigid parts and soft elements (membranes). In the folded state this configuration provides a minimal volume, which can contain the outfitting; by deployment the structure creates additional volume for a habitat.

The configuration provides a solution to keep the front faces of the structure airtight. But a suitable folding scheme for the top and bottom areas, where three foldable membrane parts are meeting in one point, has not yet been developed.

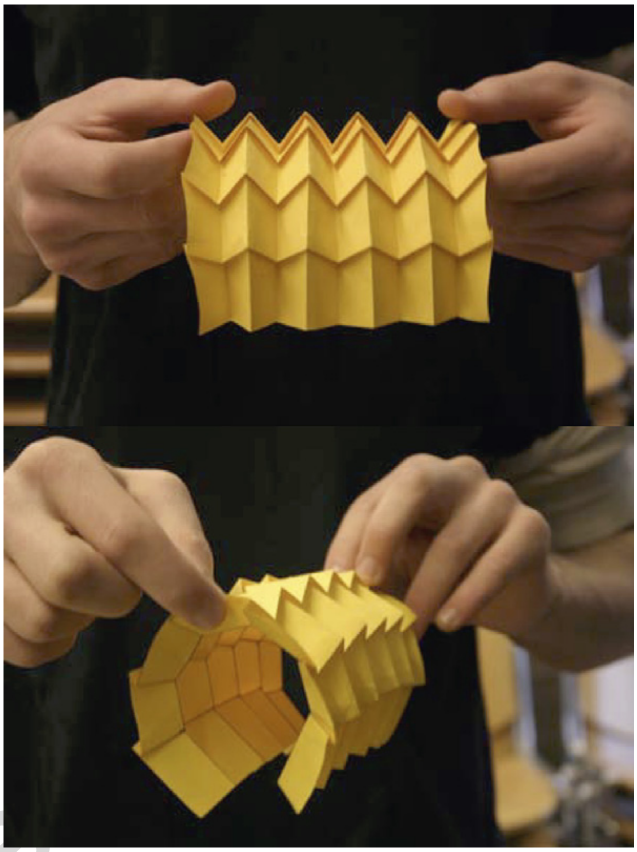

Fig. 11. Mussel shell, paper model showing deployment process.

Mussel shell (Fig. 11): Depending on the angles, the distance and number of folds across the arches, this system can generate a closed tube volume.

Pineapple folding (Fig. 12): The structure is an assembly of simple flat squares, folded and put together in alternating rows. The squares are folded along their diagonal. The endpoints of the midlines are then folded inwards, building four triangles of the same size. The midpoint is low, whilst the surrounding edges generate highpoints.

Tensegrity structures (Fig. 13): Within tensegrity structures compression and tension are permanently in balance. They combine a set of discontinuous compression struts and a continuous system of tension strings.

There are different ways of deploying the construction. The most evident one is to induce compression to the struts. A second method induces tension to the strings. The second way provides the possibility to deploy the construction by pulling on one single string, which is leading through the whole construction. The introduction of pneumatic elements would allow geometric control in the deployment phase.

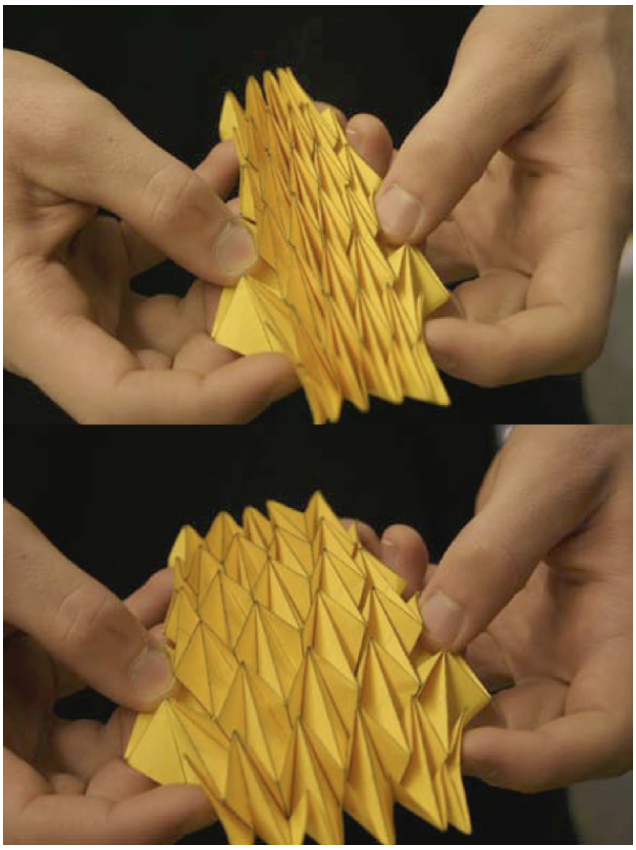

Fig. 12. Pineapple folding.

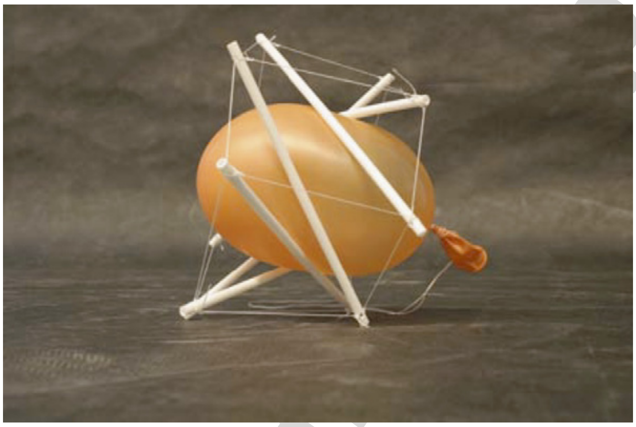

Fig. 13. Pneu-stabilized tensegrity structure.

8. Evaluation of candidate geometries

From the described set of working models candidate geometries were developed and evaluated.

The main selection criteria for identifying the most promising working models are the following:

- Deployment (regarding the ease of deployment through minimal actuation).
- Connections including hinges and sealing (if the geometry generates a sealed three-dimensional volume).
- Suitable for pressurized volume (with the possibility of a basic infrastructure such as life support system already in place when first deployed).
- Structural efficiency (can geometry integrate a load bearing structure).
- Transportation in conventional rocket (regarding efficiency in packing and storage in a state-of-the-art launch vehicle).

A matrix shows the evaluation of the selected geometries (see Fig. 14).

The candidate geometries chosen from the trade-off matrix are:

- Ladybird I–III.
- Cactus I–III.

They were chosen because they appeared to be the most promising regarding their deployment characteristics. Ladybird III and Cactus III are especially promising for further development.

9. Mechanical issues and constructive concepts

The next steps included a closer investigation of the mechanical issues and constructive concepts of the previously identified candidate geometries (Ladybird I–III and Cactus I–III). In the following an overview is given for the main general topics relevant for mechanical issues and constructive concepts.

- Hybrid/non-hybrid design.
- Folding and bending.
- Hinges and connections including sealing.
- Actuator systems.
- Rigidization.
- Radiation shielding.

Folding and bending: For deployable structures good folding strategy and mechanisms are important. A selection of the main issues are identified.

In Figs. 15–18 the desired folds for membrane structures and hard panels and their problems are shown.

There are problematic issues to tackle when folding and bending during packing for launch and deployment. When using hard panels for designing a deployable habitat an airtight flexible connecting structure has to be introduced. When using an inflatable membrane structure the bending points have to perform according to the

	Deployment	Connections, hinges/ sealing	Suitable for pressurized volume	Structural efficiency	Transportation in conventional rocket
Ladybird I	++	-	-	+	0
Ladybird II and IIa	++	0	0	+	++
Ladybird III	++	++	++	++	++
Cactus I	++	0	0	+	+
Cactus II	++	+	+	+	+
Cactus III	++	++	++	++	++
Mussel Shell	+	-	- -	0	- -
Pineapple Folding	+	-	- -	-	0
Folded Boxes	+	++	-	0	-
(Deployable) Tensegrity Structures	-	0	N.A.	++	+
Rolled-up Structure	+	+	- -	-	+

Legend: ++ very good, + good, 0 neutral, - poor, - - very poor

Fig. 14. Trade-off matrix for selected geometries.

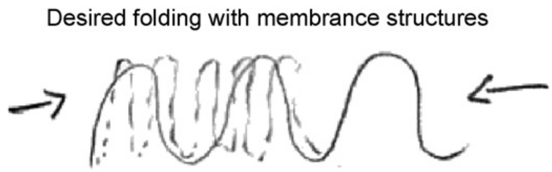

Fig. 15. Folding membrane structures.

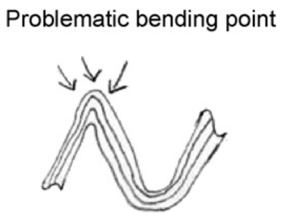

Fig. 16. Problematic bending point.

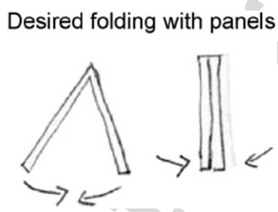

Fig. 17. Folding hard panels.

stress upon the material. Because a multi-layered membrane has a specific thickness efficient folding methods have to be developed. A biomimetic approach could help solving these issues, concerning i.e. non-hybrid material technology and use of fibrous materials.

Diagrammatic solutions for the layer structure: For the constructional details and solutions for hinges and connections the Transhab approach were merged with a

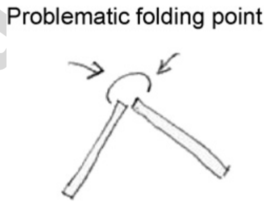

Fig. 18. Problematic folding point.

research conducted at the NASA AMES Research Center in 2004 [1]. This research introduces carbon–carbon as material for good radiation protection.

The Transhab shell structure is built as follows:

- Inflatable shell approx. 0.4 m multi-layered (from inside to outside).
- Innermost layer: puncture- and flame-resistant, protection of triply redundant bladder layers.
- Woven restraint layer: supports the bladder.
- Kevlar fabric: debris catcher and multiple layers of ceramic fabric (separated by open-cell foam), restraint layer's and bladder's protection from micrometeorite impact.
- Open cell foam.
- Outermost layer: multi-layer insulation (MLI) and atomic oxygen (AO) protective layers.

The Transhab structure and materials proved to be a protection against radiation and micrometeoroid impacts in Earth's orbit. For the study it was taken as paradigm for the inflatable parts of the candidate geometries. Further the single layers with their material characteristics and protection characteristics are regarded as role model for hybrid structural proposals.

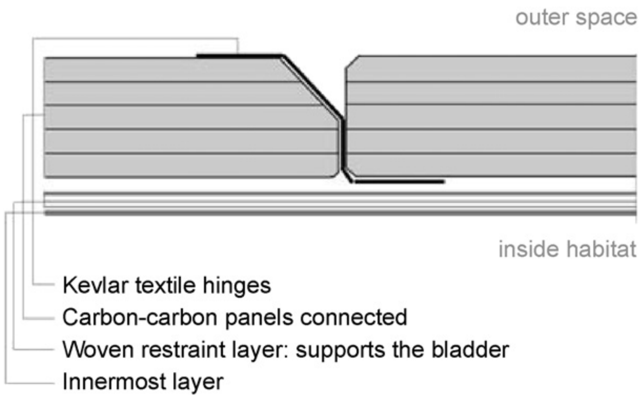

Fig. 19. Layer structure.

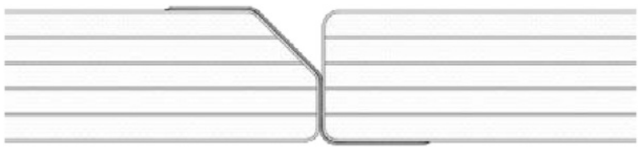

Fig. 20. Fabric Hinge option.

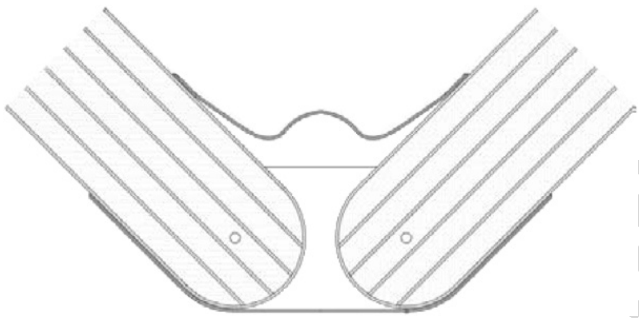

Fig. 21. Hinge option 2.

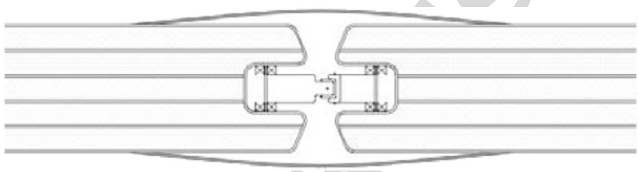

Fig. 22. Cardan Hinge.

These two research outcomes were interpreted and lead the authors to the following diagrammatic proposal for the layer structure of the deployable shell:

In Fig. 19 a diagrammatic drawing shows the proposed layer structure.

In the following options for the different developed geometries with a focus on the connection are shown.

Figs. 20–23 show details of the hinges and connections applicable to Ladybird I–II, Cactus I–II. The construction consists of a simple panel structure. Simple hinges connect the panels along their entire length. Possible solutions could be hinge-bands or a joint that connects two panels by an inserted part that allows that panels to move in a 180° angle, this movement could be restricted by an textile band (Kevlar®).

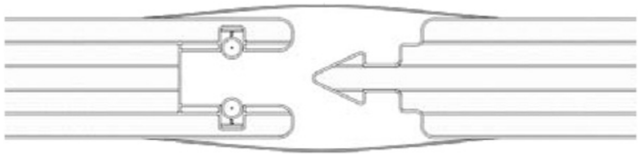

Fig. 23. Locking joint.

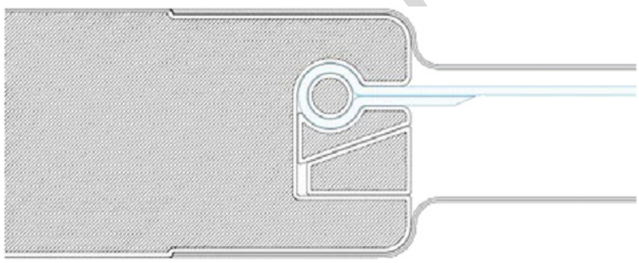

Fig. 24. Membrane stowed.

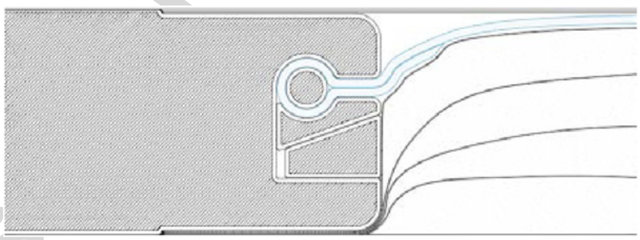

Fig. 25. Membrane inflated.

Options for the carbon–carbon panel connections are given in Figs. 21–23. The deployment implies flexibility along the hinges and the connections require to be protective against the space environment.

Textile parts form an expandable structure that connect to rigid shells. The connections have to be able to seal the structure and to carry the entire load of deployment, movement (in case of changing site location during long term missions), air pressure and habitation. They do not vary in between the structure.

Due to the required membrane's characteristics—providing sufficient radiation, debris and thermal protection—it finally needs to have a certain thickness to be able to provide the necessary debris protection. To be able to fold a membrane with a certain thickness it is necessary to vacuumize the foam layers to reduce material thickness. After deployment, air is induced and the membrane deploys to its final configuration. The detail connection drawings of Figs. 24 and 25 are applicable to Ladybird III, Cactus III.

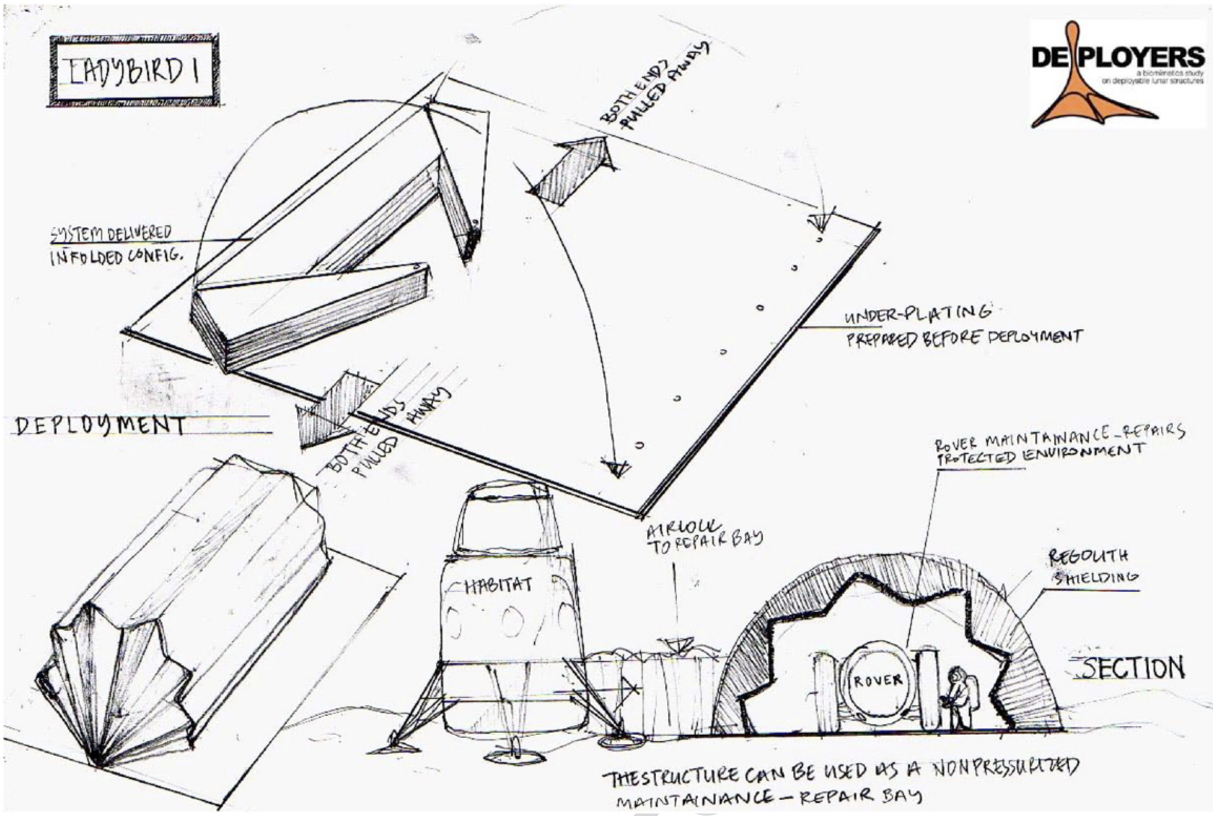

Fig. 26. Ladybird I possible applications.

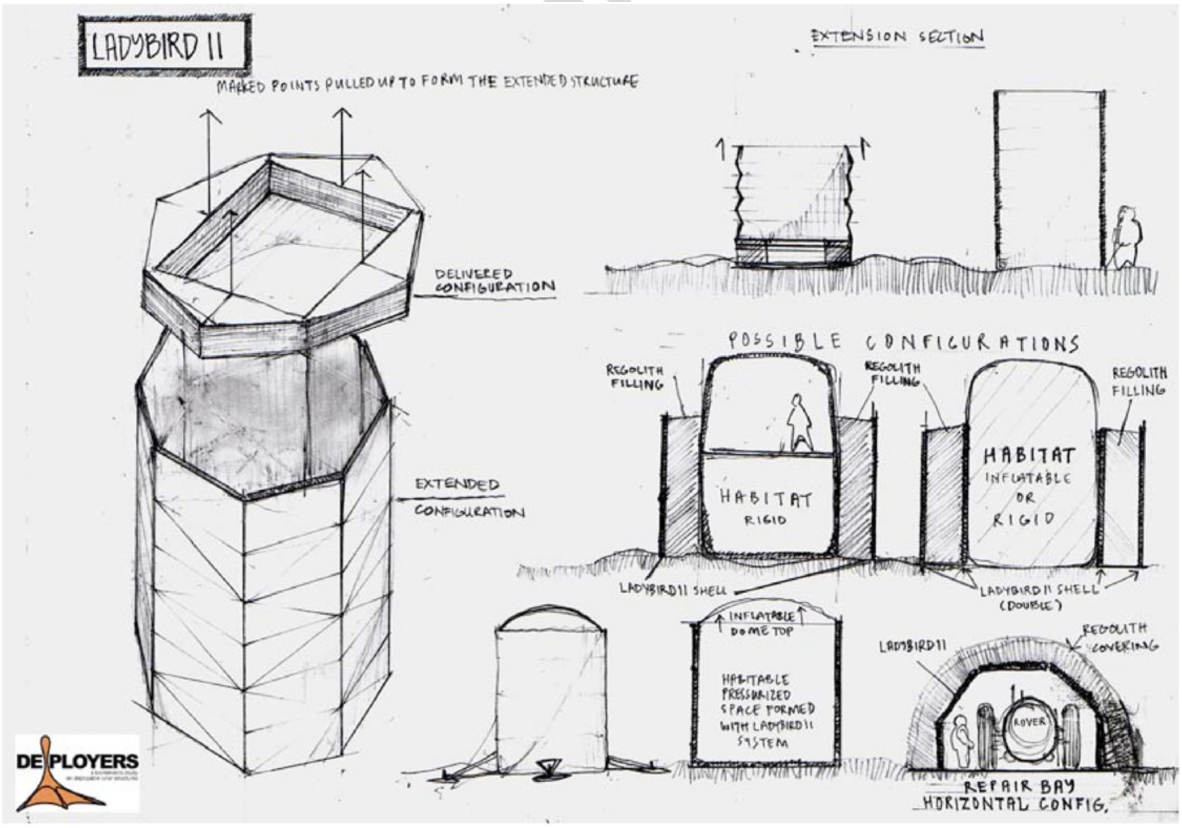

Fig. 27. Ladybird II possible applications.

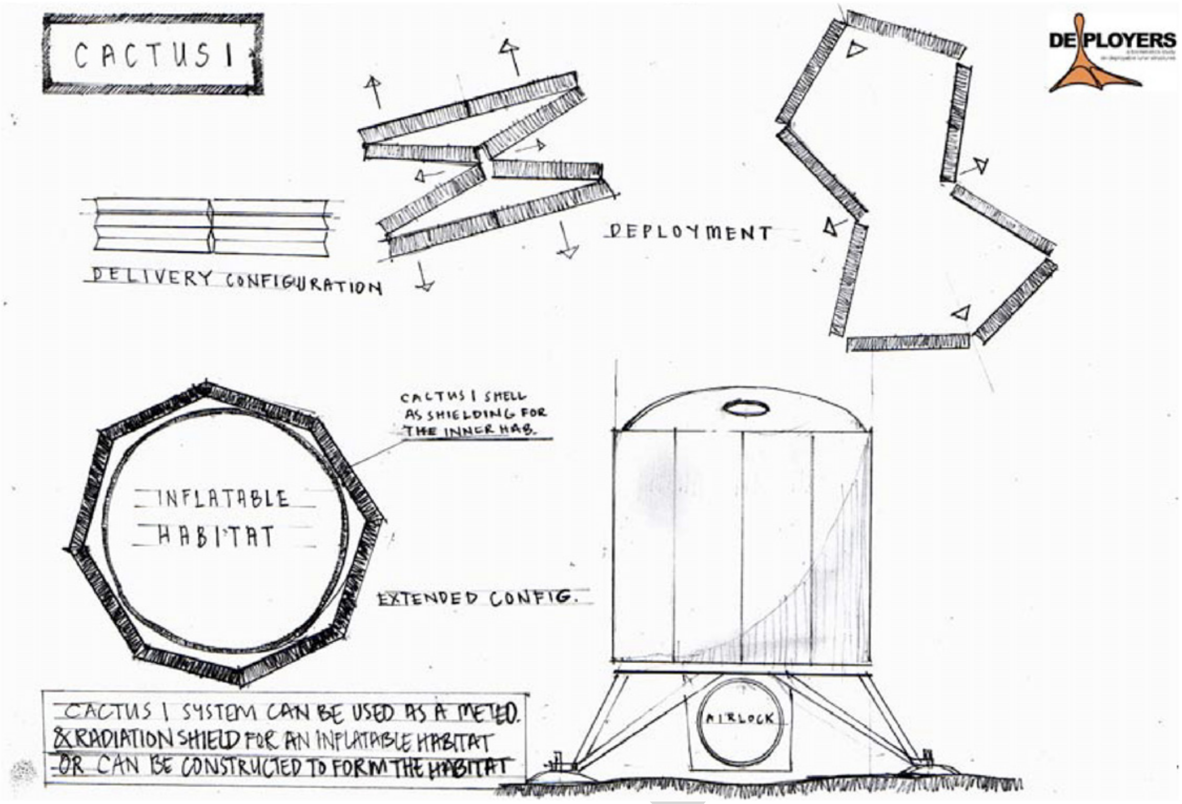

Fig. 28. Cactus 1 possible applications.

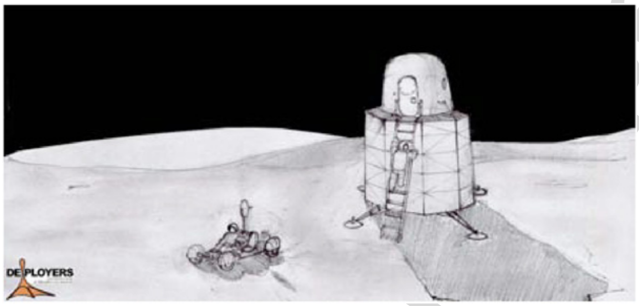

Fig. 29. Mission scenario step 1—First outpost using Ladybird II application to outer shell.

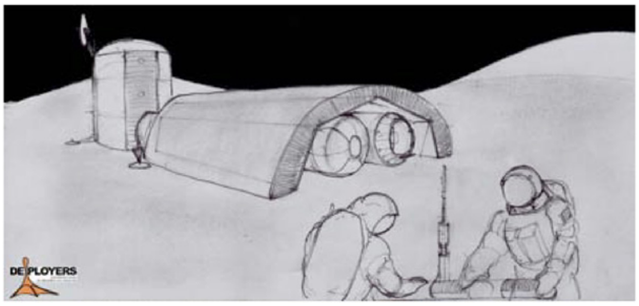

Fig. 30. Mission scenario step 2—First outpost and workshop/garage using Ladybird I application to create the non-pressurized workshop.

10. Summary and outlook

In the following section the developed designs are set into context with the ESA reference missions for the Moon. The reference Scenario refers to the "Earth Orbit Rendezvous–Lunar Orbit Rendezvous (EOR–LOR), Exploration Systems Architecture Study (ESAS)". This summarizes the outcome of the study.

Ladybird I (see Fig. 26): could be implemented as a non-pressurized maintenance–repair bay.

Ladybird II (see Fig. 27): could be used to construct habitable space providing advanced shielding and as an additional shielding for existing Habitats.

Cactus I (see Fig. 28): can be used as an additional shielding against micro meteorite impacts and radiation protection for an inflatable habitat. Cactus I can be used to construct the habitat using ISRU.

In Figs. 29–31 a possible evolution of a lunar long duration mission establishing human presence on the Moon is described. The structural technologies used for deploying the Lunar base and its adjacent infrastructure needed when growing over time is derived from the study and described in the following.

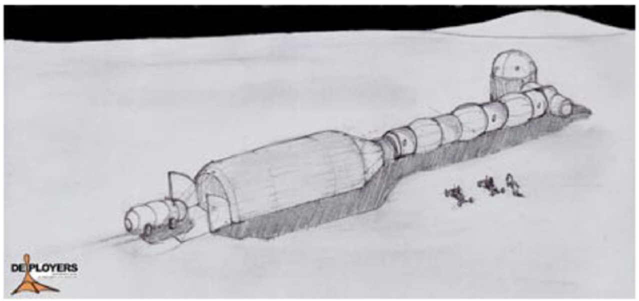

Fig. 31. Mission scenario step 3—Large outpost using Ladybird III application to create an extension to the first habitat (refer to Fig. 24) and connecting to the non-pressurized workshop (maintenance bay).

11. Conclusion

The issues raised in this paper aim at an alternative approach to deployable lunar bases deriving from concepts from nature which are most economical and thus suited for the scarce environment of spaceflight.

Recently, in the course of writing this paper a page on the Alcatel website (see Ref. [2]) has been issued which already confirms the validity of the concepts developed in the frame of the Lunar Technology Study awarded to the study team and submitted to Alcatel Alenia Space. The article "International Space Station Habitable Modules: Developing Human Life In Space" talks about Alcatel Alenia Space's contribution to Human Spaceflight and shows inflatable structures derived from the study described in this paper as first paradigms for future development and exploration.

The next steps within this research field include large scale mock-ups for testing the deployment processes and further research into material and connection technologies.

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