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DLR ADVANCED STUDY GROUP: KUBE² - ANALYSIS ABOUT THE POSSIBILITIES OF KUIPER BELT EXPLOITATION AND EXPLORATION

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At the Bremen Institute of Space Systems of the German Aerospace Center (DLR) and within the Department of System Analysis Space Segment (SARA) a group for investigating new and future space concepts has been founded in late 2010 – the Advanced Study Group (ASG). One of the topics investigated in its third instalment has been the Kuiper Belt Exploitation and Exploration (KUBE²) analysis, which involved review of the possibility to explore and exploit the Kuiper Belt e.g. for positioning of space stations, telescopes or a GPS analogue positioning system for the whole solar system.

This paper describes the results of innovative concepts for exploiting the resources available in the numerous bodies of that solar system region after a short description of the available materials given by the Kuiper Belt Objects' composition. One concept e.g. describes the application of self-replicating spacecraft to gather and transport resources from this region to other areas of the solar system or create on-site infrastructure. Another investigates the idea of using the belt as a staging ground for a number of satellites establishing a solar-system positioning system (SPS). Also the possibility to conduct science missions is regarded.

Trade-offs, calculations and initial analyses on feasibility are presented along with a thorough review of the Kuiper Belt environment and current technology especially regarding mining and manufacturing autonomously. The paper finishes with a scenario on how to best use the Kuiper Belt to further exploration of the solar-system and possibly even beyond.

I. INTRODUCTION

In late 2010 a study group for investigating innovative concepts regarding space technology has been introduced at the German Aerospace Center (DLR) in Bremen and labelled the Advanced Study Group (ASG). Consisting of a mixture of students and research staff of the Institute of Space Systems the goal is to erase fiction from presumably "science fiction" ideas. For terms of 6 months a team of three to four students investigates something like two to three topics under the tutelage of several scientific staff members. More information about the ASG and its work processes can be found in [1].

One topic of the 3rd ASG generation in the winter term of 2012/2013 has been the Kuiper Belt Exploitation and Exploration (KUBE²), which investigated the possibilities to access, explore and use the Kuiper Belt and its resources to benefit a solar system infrastructure and further solar system science.

Ideas have been setting up a solar system positioning system similarly to Earth's GPS, undertake scientific missions to e.g. Sedna or mine the asteroids autonomously. The trade-offs and analyses regarding these ideas are summarized in this paper.

I.I Motivation

The environment in the Kuiper Belt differs significantly from typical planetary environments, e.g. there is little gravity or solar illumination. Also they contain an abundance of water and other volatiles [2], which are valuable as e.g. source for fuel. Also the Kuiper Belt is the threshold to the solar system and the resources there could help to facilitate missions within the general solar system or even beyond it.

I.II Study Objectives and Assumptions

The basic objective for this study has been to investigate how the unique resources and position of the Kuiper Belt can be used to enable missions or what kind of missions could be targeted at the Kuiper Belt to utilize its unique attributes (location and resources). The assumption has been that such missions would take place in a distant timeframe, where e.g. autonomous spacecraft operation is already common place.

II. KUIPER BELT

The Kuiper Belt, also known as Edgeworth-Kuiper-Belt, has been a theory since the mid-20th century, but evidence for its existence has only been found in 1992 [3], namely 1992 QB_1. Objects that comprise the Kuiper Belt are usually just referred to as Kuiper Belt Objects or short KBO. Their variety is significant and their number likely exceeds that of the main asteroid belt, rough estimates assume that more than 100,000 KBOs with a diameter of more than 100 km exist [4]. It extends from about 30 to 50 Astronomical Units (AU). [5]

Since its reclassification as a dwarf planet and the discovery of similar bodies, e.g. Eris, Pluto is considered a KBO [6].

II.I Orbit Considerations

The Kuiper Belt is most densely populated between the 2:3 and the 1:2 Neptune resonances (ca. 40 to 48 AU) [7], although due to Neptune's influence the region between 40 and 42 AU is considered to be instable over long periods [8]. KBOs have inclinations of up to 40 degrees [9].

Three groups of bodies are usually differentiated in the KBO group:

1. Classical Belt: Members are outside of the Neptune resonances (42-48 AU) and have undisturbed orbits. Contains about two thirds of all KBOs [10]. "Dynamically cold" members have near circular orbits with inclinations below 10° [11]. "Dynamically hot" members have orbits with up to 30° [11].
2. Plutinos: Objects of this group have orbital period resonances of 1:2 or 2:3 with Neptune (including Pluto), less common are e.g. 3:4 resonances and others [12].
3. Scattered Disc: These KBOs have eccentricities of 0.8, perihelion distances of larger than 30 AU, aphelions of up to 100 AU or more and inclinations of up to 40°. [9]

II.II Body Composition

The larger KBOs have been investigated with spectrometers, which show four distinctions. There are Methane rich spectra, water-ice rich spectra, water-ice spectra with methanol and featureless spectra. [13]

Presence of water also suggests presence of hydrocarbons, e.g. C_2H_6 as is the case with Makemake and Quaoar, likely also Pluto, caused by cosmic radiation [14]. The bulk material of the bodies has not been measured yet but it is usually expected to be silicates or sulphides [15].

III. CONCEPT DESCRIPTION

Table 1 gives an overview of the mission and system ideas generated during a brainstorming by the study group at the beginning of the study. All missions have been labelled with a scale – basically describing the mission size – and a category, to sort it according to its use (e.g. scientific or exploitation, the latter referring to the exploitation of resources in the Kuiper Belt). To reduce the amount of concepts to a number, which is easier to handle a preliminary analysis has been conducted.

	Concept	Scale	Category
1	Harbor, factory and re-fuelling station for interstellar missions	interstellar	Exploitation
2	Mining for outer solar system usage	interplanetary	Exploitation
3	Observatory	local	Scientific
4	Factory for interstellar robotic explorers	interstellar	Exploitation/ Scientific
5	Factory for outer solar system robotic explorers	interplanetary	Exploitation/ Scientific
6	Touristic cruise	interplanetary	Crewed
7	KBO for terraforming	interplanetary	Terraforming
8	Solar System wide positioning system: SPS	interplanetary	Positioning
9	Build a starship inside a KBO	interstellar	Crewed
10	Self-replicating precious metal collectors	interplanetary	Exploitation
11	Fuel station and production for trans-martian or trans-Jovian missions	interplanetary	Exploitation
12	Using a KBO as a tethered weight for artificial gravity generation	interstellar	Crewed
13	Dedicated Sedna mission	local	Scientific

Table 1: Pool of concepts for KUBE².

III.I Preliminary Considerations

Based on the long travel durations to the Kuiper Belt, touristic attraction can be eliminated (concept 6) and also any crewed mission. Compared to interstellar distances the distance of the Kuiper Belt is small, therefore its use as intermediate destination is insignificant. Consequently all interstellar scaled missions are eliminated from the list as well.

Applying resources from the Kuiper Belt for terraforming Mars has been considered too ambitious (taking a huge amount of time to generate results) and specific for further study.

The observatory would be prefabricated system and therefore would not exploit the Kuiper Belt location or if it were fabricated in the belt, the technology and processes for this would not differ from those investigated for the other mission concepts presented later. In any case the low temperature environment and proximity to the belt and Oort Cloud would likely facilitate the observation of small bodies in these areas of the solar system.

Sedna has a very eccentric orbit (0.85) and a perihelion of 76 AU. Its next perihelion passage occurs in 2075 (orbital period is 11.400 years), which is a unique opportunity to study this celestial body. [16] Nonetheless it is a rather traditional mission (body rendezvous) and therefore not considered further in the KUBE^2 study.

III.II Selection and Mission Guidelines

The remaining concepts are considered to be rather similar, mostly concentrating on exploitation, not including the positioning system (concept 8), although some components might be similar for this kind of mission purpose and an exploitation mission (e.g. transfer vehicles).

The exploitation scenarios are evaluated as a basic default mission, using similar components. This basic mission has to produce:

- Power
- Satellites
- Rovers

and all of this *in-situ*. It should further be able to extract resources autonomously.

IV. BASIC MISSION LAYOUT

The basic mission layout is assumed to be a “semi-self-replication”. An autonomous factory is sent to the Kuiper-Belt. It then creates rovers for resource gathering and exploration, which allow it to create more rovers and more spacecraft in turn.

IV.I Transfer to Kuiper Belt

The most simple way to reach the Kuiper Belt would be a Hohmann transfer, a half ellipse between two circular, concentric and coplanar orbits – naturally only at the expense of considerable flight times [16]. Assuming these, a Hohmann transfer results in a ΔV of 12 km/s and a flight time of 45 years (assuming a target orbit radius of 40 AU).

As a next step the departure velocity has been increased stepwise, the results are presented in Fig. 1. For these calculations it was assumed that all orbit transfers occur in the same plane (coincident with the elliptic) and a mission start from LEO and that transfer consists of two manouvers: one for leaving the Earth LEO and insert onto a direct transfer to the KBO and another for stopping and making the orbit circular with a=40AU.

The ΔV reaches values above 19 km/s for transfer times of ca. 15 years. Figure 1 also shows that for a moderate ΔV increase of about 2 km/s the flight time is reduced by ca. 50% (in comparison to the Hohmann Transfer) to 22 years.

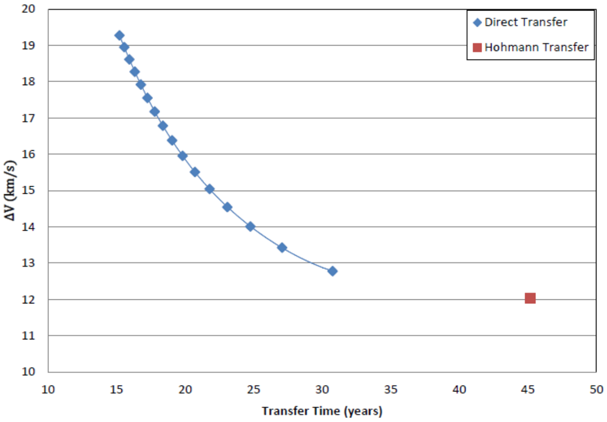

Fig. 1: ΔV requirements for direct transfer in dependence on transfer times.

In further calculations swing-by manoeuvres at Jupiter have been considered as well, however the need to adapt the velocity required for the orbit insertion at Kuiper Belt increases the ΔV again. In general, application of a swing-by at Jupiter reduces the time of flight for a given ΔV. Optimization of a trajectory was however deemed outside the scope of the study as an actual mission time and target has not been selected and therefore any specified mission analysis would become obsolete once the mission should be planned.

For low-thrust engines the ΔV requirement can be obtained by subtracting the different circular velocities of launch and target orbit [17]. Assuming once more a target solar distance of 40 AU and Earth’s orbit as launch orbit, this results in a ΔV of 25 km/s.

In order to exploit the Kuiper Belt for the set-up of infrastructure, especially for gathering resources it needs to be investigated what ΔVs and what transfer times occur for transfers within the belt.

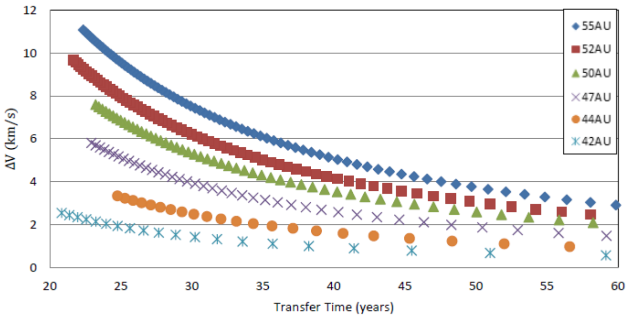

Fig. 2: ΔV requirements and resp. transfer times for direct transfers within the Kuiper Belt to various locations from an Orbit of 39 AU radius.

Analogue to the previous calculations, transfers for chemical propulsion have been calculated and are summarized in Fig. 2. It is obvious that the transfer times are significant – further increase of the departure velocity, can reduce e.g. the transfers from Pluto to Haumea down to 8 years at a ΔV of 11 km/s.

Regarding system complexity, electrical engines are considered to be more complex and are therefore not favourable for a self-reproducing spacecraft infrastructure. Consequently this concept is not considered further.

IV.II Power

For the different phases of the mission three kinds of power systems are needed. One for the initial transfer vehicle and factory, one which can be created in-situ and used by the fabricated follow-on missions and one which can be used by the rovers roaming the small bodies and extracting resources.

For the former two systems a maximum power of 300 kW has been selected as a first estimate for such a complex system to be operated (vehicle and factory). The rover system is targeted at a power demand of 200 W.

The lifetime for the factories (original and fabricated) has to be significant to justify the production effort, therefore strongly degrading technology cannot be used for these power systems. They also have to be productive at a solar distance equivalent to the Kuiper Belt (solar constant for the Kuiper Belt varies between 1.52 W/ m² at 30 AU and 0.38 W/m² for 60 AU).

Various power sources and storages have been investigated, e.g. radioisotope thermoelectric generators (RTG), solar power (SP), fly wheels, batteries or micro-wave power beaming [18].

Answering requirements in mobility, reliability, in-situ operation and low complexity, the fuel cell is selected for usage in the rover.

Due to the availability of water (and Deuterium) and the large amount of power generable, a fusion reactor has been selected for usage in the main spacecraft and factories.

The overall system will start with mining water ice. This water ice will contain the deuterium and in a processing plant the ice will be melted and the deuterium will be separated. The deuterium will be fed into the fusion reactor, which will deliver electrical power and heat to the processing plant. The excess hydrogen and oxygen are used for the miners and rovers. With a Sabatier reaction the hydrogen, using carbon dioxide as input, can be transformed into methane, for easier storage.

IV.III Resource Extraction

Investigating various mining methods, under consideration of criteria like applicability in the substrate (boulders, regolith, ices), environment, consumables, complexity and depth, the main mining method has been selected as a cold trap for volatiles. Via radiating heat onto the body surface, volatiles are evaporated and come into contact with plates, which have the environmental temperature (cold), therefore the volatiles condensate again and can be further transported into fabrication. A sketch of such a method is given in Fig. 3.

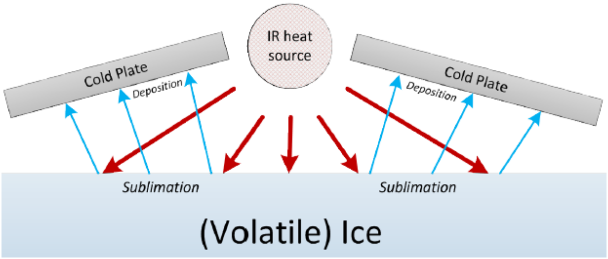

Fig. 3: The cold trap ice mining method. A heat source heats the ice, which sublimates, contacting cold plates, causing condensation. The captured volatiles can be transported, liquefied in a closed pressurized container or scraped off into a larger holding container.

Core drilling is envisioned for material extraction in deeper regions [19] and a simple scoop for collecting regolith.

IV.IV In-situ Manufacturing

The main topics for the in-situ manufacturing are the questions of materials and processes to be used for e.g. recreating spacecraft or other systems out of the resources available at hand in the Kuiper-Belt.

As the major commodity for usage as a production resource carbon nano-tubes (CNT) have been selected, due to their versatile properties [20]. For production of the CNTs, chemical vapour deposition is envisioned as it is a simple and cheap process.

CNTs can be used for e.g. ion thrusters production [21], electronics [22] and generally as structure material.

Another major component to be created in-situ is fuel. A list of possible propellants includes:

- Hydrogen (H_2)
- Hydrogen Peroxide (H_2O_2)
- Methanol (CH_3OH)
- Methane (CH_4)
- Hydrazine (N_2H_4)

Especially Hydrogen Peroxide and Hydrazine can be used as monopropellants, which would be favourable in terms of complexity of a space system, but production of both is complicated.

As a very versatile production method 3D printing is investigated to be used for reproducing the spacecraft autonomously. The major obstacle is whether or not this technology can be used in zero- or microgravity environments.

Advantageous is the flexibility of the process and the ability to create versatile shapes of system components.

Currently three methods for space-based 3D printing are being developed [23]:

- Electron Beam Fabrucation (EBF3)
- Selective Laser Sintering (SLS)
- Fused Deposition Modeling (FDM)

EBF3 is known to work with typical space alloys and currently has the most potential for actual application – its current version uses 3 kW of power, the resolution of the process is limited to the mm-range. However it has been proven in a zero-g-environment [23].

Critical areas are mostly the system size, reproduction of electronics and circuits and the power demand.

V. SOLAR SYSTEM POSITIONING

For an increase in interplanetary operations a system for autonomous navigation would allow spacecraft to determine their position without interaction with a ground station. Therefore in the frame of this study a system analogously to the Global Positioning System (GPS), dubbed Solar-System Positioning System (SPS) has been investigated.

Just like with GPS, the SPS will transmit a signal, which can be received by any spacecraft (with the right equipment) to determine its position.

V.I Link Budget

For analysis of the link budget, the basic link budget equation is applied [24]:

$$\frac{Eb}{No} = \frac{P_t G_t G_r L_l L_a L_s}{k T_s R} \quad (1)$$

where E_b/N_o is the ratio of the received energy-per-bit to noise-density, P is the power, G is the antenna gain in linear units, L_l is the transmitter to antenna loss in linear units, L_s is the space loss which be determined by the path length between the transmitter and the receiver in linear units, L_a is the transmission path losses due to atmospheric attenuation (e.g. rainfall density and galactic noise) in linear units, k is the Boltzmann constant ($1.380 \cdot 10^{-23}$ J/K), T_s is the system noise temperature and R is the data rate, in bits-per-second.

Antenna Diameter [m]	Power [kW]	No. of Satellites
11.7	100	824
6.7	300	475
5.2	500	367
4.4	700	309
3.9	900	272

Table 2: Overview over satellite numbers and parameters for a layered SPS configuration.

The subscripts “t” and “r” belong to the transmission and reception parts, respectively.

A typical value for the minimum bit error rate is 10^{-5}, which is determined by the signal to noise ratio [24].

In order to obtain a high antenna gain, a parabolic shape is selected – with power values ranging from 100 kW to 1 MW, it became apparent that the antenna size would range between 50 and 150 m, therefore a different approach for the layout has been selected, which will be described in the next subsection, the major driver for this being the free space losses.

V.II Constellation Layout

To reduce the required power, antenna diameter and the number of satellites an effective satellite layout is needed. Therefore a layered configuration of the satellite constellation is investigated, to obtain a high coverage of the solar system, see Fig. 4.

This layout allows a full coverage within Jupiter’s orbit radius, less in the outer solar system. The coverage can obviously be increased with a larger satellite number – of course also increasing effort in launches and costs.

For this configuration the decreased requirements in satellite signal range (due to layering the satellites) the transmitter power and antenna diameter can be decreased at the increase of satellite number, which is listed in Tab. 2.

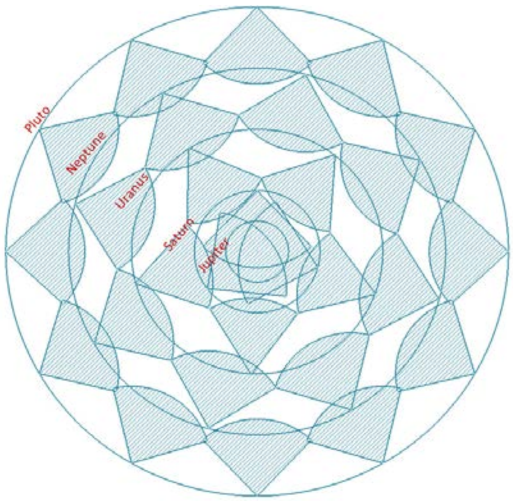

Fig. 4: An example of a layered satellite configuration.

V.III Conclusion on SPS Validity

Currently – due to the large amount of power required and the huge number of satellites, the SPS is not considered a valid option.

VI. EXPLOITATION AND EXPLORATION

VI.I Architecture

Via an analytical hierarchy process (AHP) a reasonable mission architecture has been determined for exploring and exploiting the Kuiper Belt.

The basic mission idea has already been described in Section IV, using the AHP this layout has been further defined.

Several spacecraft with prefabricated factories, one mining and one explorer rover are sent to different Kuiper-Belt objects, where they will set down and the mining rover will start to gather resources while the explorer surveys the object. These resources are used to create more rovers, until enough resources can be gathered to create a new factory. This will further increase the production speed to set up a real network for resource extraction. Ultimately the factory network will have enough resources to produce an orbiter that is able to map the object, i.e. further the survey of the KBO. As a next step – once the production rate is large enough – transporters can be created that transfer resources to different points of interests within the solar system, e.g. to planetary outposts or space stations.

VI.II Factory Design

The factory will be separated into several units. The chemical sector is used for processing the resources, the fabrication unit creates the products, the assembly sector is responsible for assembly while the storage unit stores resources and products. An overview of this process is shown in Fig. 5.

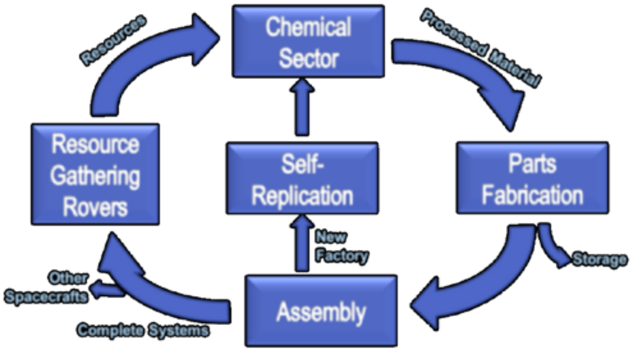

Fig. 5: Process cycle of the factory growth.

The complete mass of this factory is assessed to 10.000 kg in total, where the chemical sector is the driver with about 3.500 kg (e.g. consisting of a reactor, heating systems, pressure system and an energy source).

VI.III Spacecraft Design

Besides the factory four more systems are part of the mission architecture (mining rover, explorer rover, orbiter, transport). They are shortly described in this subsection.

Mining Rover

This component of the mission architecture extracts the resources from the KBO and transports them to the factory. It is equipped with a core drill, a cold trap and a collecting scoop (s. Fig. 6). An infrared camera is used for navigation (visual is likely not feasible due to the little amount of sunlight) and material identification. Summarized the payload is assumed to have a mass of 450 kg and a power demand of 500 W. Overall the rover has a size of 2200 kg (with 30% margin) and 1850 W of power. The sizing is based on [25] and [26].

Fig. 6: A preliminary draft of a mining rover with a cold trap (aft section, grey) a reservoir for storing (blue), a scoop for collecting regolith and a drill.

Explorer Rover

The explorer is mainly searching for resources, therefore it is designed to be light and fast. It has the ability to sample the surface and analyse the sample using a microscope and a spectrometer. Deeper analysis is conducted with a sounding radar.

The payload has a mass of 75 kg and a power demand of ca. 200 W, whereas the complete systems has masses about 370 kg and has a power demand of 700 kg. A draft image is presented in Fig. 7.

Fig. 7: A simple draft of an explorer rover.

Fig. 8: A simple draft of an orbiter spacecraft, clearly visible the propulsion system (right) and the high gain antenna (left) as well as the payload (center).

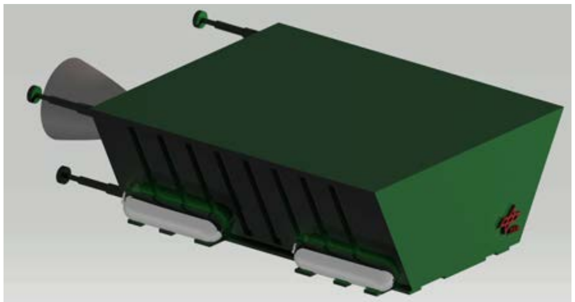

Fig. 9: A simple draft of a transport spacecraft.

Orbiter Spacecraft

The orbiter complements the explorer's ability to survey the KBO, increasing the amount of surface area that can be explored. It furthermore serves as a relay and means to coordinate the rovers and the factory.

The major difference to the rovers is the need for a rocket propulsion system for orbit insertion and control. The instruments are similar to those of the explorer, but with larger range, therefore they have a total mass of 120 kg and consume power of about 320 W. In total it is assumed to have a mass of 470 kg and a power demand of 1200 W. The spacecraft is shown in Fig. 8.

Transporter

The transporter is a very simple spacecraft, which conveys the gathered resources to other solar system regions. For an initial design a payload capacity of 200 kg is assumed.

A draft layout is shown in Fig. 9. The total mass of the system is assumed to be 540 kg, the power demand 535 W.

VI.IV Timeline

Right from the start, a distant timeframe has been one major assumption during the KUBE² study. Considering the essential technical demands of the mission, e.g. autonomously (re)production of spacecraft, for a launch date the year 2065 has been assumed (approximately 50 years from now). With reference to Section 3.1, about 15 years later (ten years with Jupiter swing-by) the spacecraft would arrive at the first KBO target. There the next steps are:

- Construction of 2nd mining rover (therefore doubling the speed of resource gathering): **2085**
- Construction of 1st orbiter (after establishing a "fleet" of mining rovers): **2100**
- Construction of 2nd factory onsite (after reaching the limit of 1st factory that transferred from Earth, 2nd factory gets on timeline, identical to 1st): **2120**
- Self-replication of 2nd factory: **2150**
- 1st transport ready to transfer resources into other solar system regions: **2170**
- Working resource delivery service: **2180**
- Creation of SPS: **2200**

VII. OPEN ISSUES

One cornerstone of the study is the ability of self-replication. Currently 3D printers are incapable of manufacturing 100% of their own parts, i.e. the proposed factory concept, capable of building fully functional spacecraft and itself, is still far from reality. It was assumed that this technology would be possible within the considered time frame but research and development of this topic needs to continue for that to happen, more specifically in the fields of 3D printing and carbon nanotubes manufacturing.

Power generation is another main open issue of this mission. Nuclear fusion is still in its early stages of development and, although its potential has been thoroughly researched by [27] and [28], its development is still very unpredictable and highly dependent on upcoming experiments.

Another problem comes up due to the extensive timeframe. While the cost for the initial spacecraft is likely modest and due to the autonomous nature of the spacecraft operations costs would probably also not be extensive. However the actual mission results will occur after a timeframe in the order of 100 years. This, naturally, will restrain the interest of most (if not all) space faring nations, if the outcome – i.e. the amount of resources gained – is not significant enough.

VIII. CONCLUSION

This paper summarizes a study about the exploration and exploitation of Kuiper Belt Objects within this and the next century. For this it is assumed that the corresponding spacecraft have the ability to replicate themselves and autonomously create an infrastructure to search, explore and mine their target KBO. The main purpose is to support interplanetary travel and the set-up of an infrastructure for exploitation of the resources available in the Kuiper Belt.

It is explained that current technology is not yet capable to create such spacecraft, but current developments target the necessary technical areas – e.g. by further developing 3D printing in a zero-g environment. Therefore a timeframe has been estimated that will allow this mission concept to start in the second half of this century.

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