Efficient Massively Parallel Prospection for ISRU by Multiple Near-Earth Asteroid Rendezvous using Near-Term Solar Sails and 'Now-Term' Small Spacecraft Solutions

Jan Thimo Grundmann[(1)], Waldemar Bauer[(1)], Jens Biele[(2)], Ralf Boden[(3)], Matteo Ceriotti[(4)], Federico Cordero[(5)], Bernd Dachwald[(6)], Etienne Dumont[(1)], Christian D. Grimm[(1)], David Herčík[(7)], Tra-Mi Ho[(1)], Rico Jahnke[(1)], Aaron D. Koch[(1)], Alexander Koncz[(8)], Christian Krause[(2)], Caroline Lange[(1)], Roy Lichtenheldt[(9)], Volker Maiwald[(1)],Tobias Mikschl[(10)], Eugen Mikulz[(1)], Sergio Montenegro[(10)], Ivanka Pelivan[(8)(15)], Alessandro Peloni[(4)], Dominik Quantius[(1)], Siebo Reershemius[(1)], Thomas Renger[(1)], Johannes Riemann[(1)], Michael Ruffer[(10)], Kaname Sasaki[(1)], Nicole Schmitz[(8)], Wolfgang Seboldt[(11)], Patric Seefeldt[(1)], Peter Spietz[(1)], Tom Spröwitz[(1)], Maciej Sznajder[(1)(12)], Simon Tardivel[(13)], Norbert Tóth[(1)], Elisabet Wejmo[(1)], Friederike Wolff[(9)], Christian Ziach[(14)]*

[(1)]DLR German Aerospace Center, Institute of Space Systems, Robert-Hooke-Strasse 7, 28359 Bremen, Germany – [*]+49-(0)421-24420-1107, jan.grundmann@dlr.de – [(2)]DLR German Aerospace Center, Space Operations and Astronaut Training – MUSC, 51147 Köln, Germany – [(3)]Institute of Space and Astronautical Science (ISAS), Japan Aerospace Exploration Agency (JAXA), Solar Power Sail ISAS Pre-Project, 3-1-1 Yoshinodai, Chuo, Sagamihara, Kanagawa, 252-5210, Japan – [(4)]University of Glasgow, Glasgow, Scotland G12 8QQ, United Kingdom – [(5)]Telespazio-VEGA, Darmstadt, Germany – [(6)]Faculty of Aerospace Engineering, FH Aachen University of Applied Sciences, Hohenstaufenallee 6, 52064 Aachen, Germany – [(7)]Institute for Geophysics and Extraterrestrial Physics, Technical University Braunschweig, Germany – [(8)]DLR German Aerospace Center, Institute of Planetary Research, Rutherfordstr. 2, 12489 Berlin, Germany – [(9)]DLR German Aerospace Center, Robotics and Mechatronics Center, 82234 Wessling, Germany – [(10)]Informatik 8, Universität Würzburg, Am Hubland, 97074 Würzburg, Germany – [(11)]Consultant to DLR Institute of Space Systems – [(12)]Institute of Physics, University of Zielona Góra, Szafrana 4a, 65-069 Zielona Góra, Poland – [(13)]CNES, Future Missions Flight Dynamics, 18 avenue E. Belin, 31401 Toulouse cedex 9, France – [(14)] High-Tech Gründerfonds Management GmbH, Schlegelstraße 2, 53113 Bonn, Germany – [(15)] Helmholtz Centre Potsdam, GFZ German Research Centre for Geosciences, Telegrafenberg, 14473 Potsdam, Germany

Physical interaction with small solar system bodies (SSSB) is key for in-situ resource utilization (ISRU). The design of mining missions requires good understanding of SSSB properties, including composition, surface and interior structure, and thermal environment. But as the saying goes "If you've seen one asteroid, you've seen one asteroid": Although some patterns may begin to appear, a stable and reliable scheme of SSSB classification still has to be evolved. Identified commonalities would enable generic ISRU technology and spacecraft design approaches with a high degree of re-use. Strategic approaches require much broader in-depth characterization of the SSSB populations of interest to the ISRU community. The DLR-ESTEC GOSSAMER Roadmap Science Working Groups identified target-flexible Multiple Near-Earth asteroid (NEA) Rendezvous (MNR) as one of the missions only feasible with solar sail propulsion, showed the ability to access any inclination and a wide range of heliocentric distances as well as continuous operation close to Earth's orbit where low delta-v objects reside. Also, separated payloads were considered. However, it appears difficult for sailcraft to interact physically with SSSBs. We therefore expand and extend the philosophy of the recently qualified DLR GOSSAMER solar sail deployment technology using multiple sub-spacecraft for deployment. In the same manner, landers are added for one-way investigations or shuttling sample-return. An ideal counterpart for this purpose is the MASCOT nano-lander designed for the JAXA HAYABUSA2 mission to carbonaceous NEA (162173) Ryugu. Shoebox-sized and weighing 11 kg with deployment mechanism, it is compatible with small interplanetary missions designed for piggy-back launch accommodation which enables low-cost massively parallel access to the NEA population. Its unique mobility hopping mechanism was already adapted to the specific needs of long-lived missions with the MASCOT2 design for ESA's AIM spacecraft in the NASA-ESA mission AIDA to binary NEA (65803) Didymos. A shuttling sample-return lander similar in size to PHILAE is being studied for the JAXA Solar Power Sail mission, OKEANOS. The methods enabing the realization of MASCOT such as Concurrent Engineering, Constraints-Driven Engineering and Concurrent Assembly Integration and Verification enable responsive missions based on re-used, re-purposed or now available as well as near-term technologies. Integrating these by Model-Based System Engineering (MBSE) will lead to further streamling of hardware and mission implementation. With the thus raised efficiency of mission implementation and a piggy-back launched small spacecraft approach, institutional as well as commercial asteroid users are enabled to move on from single-trail traverses to broad area surveys of the asteroid population. The ability to visit multiple targets per spacecraft and to change, even select targets only after launch also decouples the mission from the pre-launch state of ground-based target observations. The mission can grow in flight with the growth of knowledge on asteroids on the ground. While actual mining and even preparatory missions will require larger payloads, the performance of present sail technology is sufficient to undertake initial surveys, on the basis of well-established and trusted transparently peer-reviewed planetary science methods, to open up this new frontier to new enterprises.