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PYRODUCT: A PARAMETRIC TOOL FOR GENERATING REALISTIC 3D MODELS OF LUNAR AND MARTIAN LAVA TUBES

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Abstract

On the Moon and Mars, recent studies have shown the possible existence and extent of underground conduits, known on Earth as "lava tubes" or "pyroducts". Despite knowing the location of some of these features, it is not possible, at present, to assess their interior, which remains an open question. At the moment, when represented, especially in space architecture design proposals, lava tube interiors are depicted as purely notional or fictional, lacking, in most cases, a scientific rationale. On Earth, lava tubes have been studied for a long time, and lots of data are available regarding the interior assets of many of them worldwide. In particular, current research agrees that Martian and Lunar lava tubes might share similar genetic mechanisms with Terrestrial ones, with the main difference being the internal dimensions, which, in the case of Mars and especially the Moon, would be significantly bigger. In the present research, with the use of Rhinoceros's visual programming language Grasshopper 3D, we have developed an algorithm that is capable of generating accurate 3D models of lava tubes by interpolating the available data of mapped Lunar and Martian pyroducts paths with Terrestrial data. Due to the increasing interest in underground space habitats and lava tube architectures, because of their capability of shielding future settlers from environmental factors such as radiation, extreme temperatures, and the impact of micrometeorites, this paper aims to provide a tool for more realistic lava tube representations, as they would provide a more appropriate context for performing analysis and evaluations, but also for logistics and space architecture planning. Lava tubes are a terrific resource that might enhance a future sustainable space exploration: geological resources that are already available to be used and adapted for sheltering and habitation purposes are an invaluable resource that dares further investigation.
Keywords: lava tube generator, lava tube, lava tube architecture, lunar and Martian cave exploration, In-Situ Resource Utilizarion (ISRU), pyroduct.

Acronyms/Abbreviations
LRO Lunar Reconnaissance Orbiter
Mini-RF Miniature Radio-Frequency
AEC Architecture, Engineering and Construction
VPL Visual Programming Language
INGV National Institute of Geophysics & Volcanology
RS Remote Sensing
DEM Digital Elevation Model
.SHP Shapefile (file format)
.DXF Drawing Exchange Format (file format)
.CSV Comma-Separated-Values (file format)
GIS Geographic Information System
NURBS Non-Uniform Rational Basis-Splines
ISRU In Situ Resources Utilisation
NASA National Aeronautics and Space Administration
ESA European Space Agency
YAC Young Architects Competitions
NSFC National Natural Science Foundation of China

1. Introduction

Starting from the 1970s, different authors have related a variety of lunar volcanic structures – such as sinuous rilles - with the possible presence of underground conduits known as "lava tubes" or "pyroducts", defined by Halliday as "roofed conduits of flowing lava, either active, drained or plugged" [1].

On Earth, lava tunnels have been known for a very long time: different cultures around the globe used them as shelters from the weather and enemies, for prolonged habitation, storing goods - due to their stable and cool temperatures -, for burial and religious purposes. A few examples can be found in Sicily, Iceland, the Canary Islands, Hawaii, and many other global locations [1, 2, 3, 4]. Early descriptions of these structures can be found in ancient stories, such as Icelandic Holmverja and Landnama sagas, and later in the reports of 18th – 19th-century travelers and naturalists: the firsts often picturing

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these caves with fantasy and documenting the folklore, the latter noting early scientific observations [4] (Fig.1). In Sicily, thanks to scientists such as Dolomieu and Sartorius von Waltershausen, some of Etna's lava tunnels were first described and surveyed, and some tentative explanations of their possible genesis were provided. Similarly, in the Canary Islands, thanks to the geologist Georg Hartung, the Corona lava tube system, one of the biggest in the world, was described [2] (Fig.1). In Iceland, the first descriptions and possible explanations of lava tube emplacement mechanisms can be traced back to Kant's Physische Geographie [5] and Olafsen & Povelsen [3, 6], which were then followed by Troil [7, 8] and later by Henderson [3], who in 1818 suggested that lava tunnels were created by the solidification of a crust upon the lava flow. In Hawaii, Coan was the first to observe and describe 1843 an active tunnel, coining the term "Pyroduct", which might be referred to as the historical precursor of the common modern term lava tube [8, 9]

1.1 The growth of scientific thought on the formation of lava tunnels: from simplicity to complexity

Following these first experiences, many other scientists worldwide have continued surveying and studying pyroducts, often speleologists themselves or in tight collaboration with speleological groups. In particular, the traditional hypothesis suggested by Henderson in 1818 and expanded by Corbel in 1955 - that lava tubes form due to the crusting over of a lava flow in a channel - became very popular and adopted by many scientists [10, 11, 12, 13], who documented the formation of active lava tubes, especially in Hawaii, and expanded on the different ways the roof could be formed. During this time, it was also postulated that between all typologies of lava, lava tubes exclusively develop in fluid pahoehoe lava flows and not in the more viscous ʻAʻā [12]. Both typologies are characteristic only of basaltic lava flows. Soon enough, other scholars noticed that these theories couldn't account for all the observed pyroducts, shapes, and structural features [8, 14, 15, 16, 17, 18, 19], so, over the years, other lava tube genetic mechanisms have been described. It was confirmed that lava tubes not only can form in basaltic ʻAʻā lava but also even more viscous lava flows with other chemical compositions, such as andesite and rhyolite lava flows [1, 17, 18].

1.2 The discovery of lunar and Martian caves

From the late 1960s and early 70s, the study of pyroducts witnessed a great resurge which still lives to the present time. This was first due to scientists such as Oberbeck and Greeley, who noted that some lunar volcanic features, such as sinuous rilles and chains of elongated craters (Fig.2) - which were pictured during the Apollo missions 1969-1972 - had very similar characteristics to Terrestrial lava channels and lava tubes [20, 21]. More recently, in the area of Marius Hills - the same observed by Greeley in 1971 – Haruyama et al. observed the first lunar pit [22] (Fig.2). Since then,

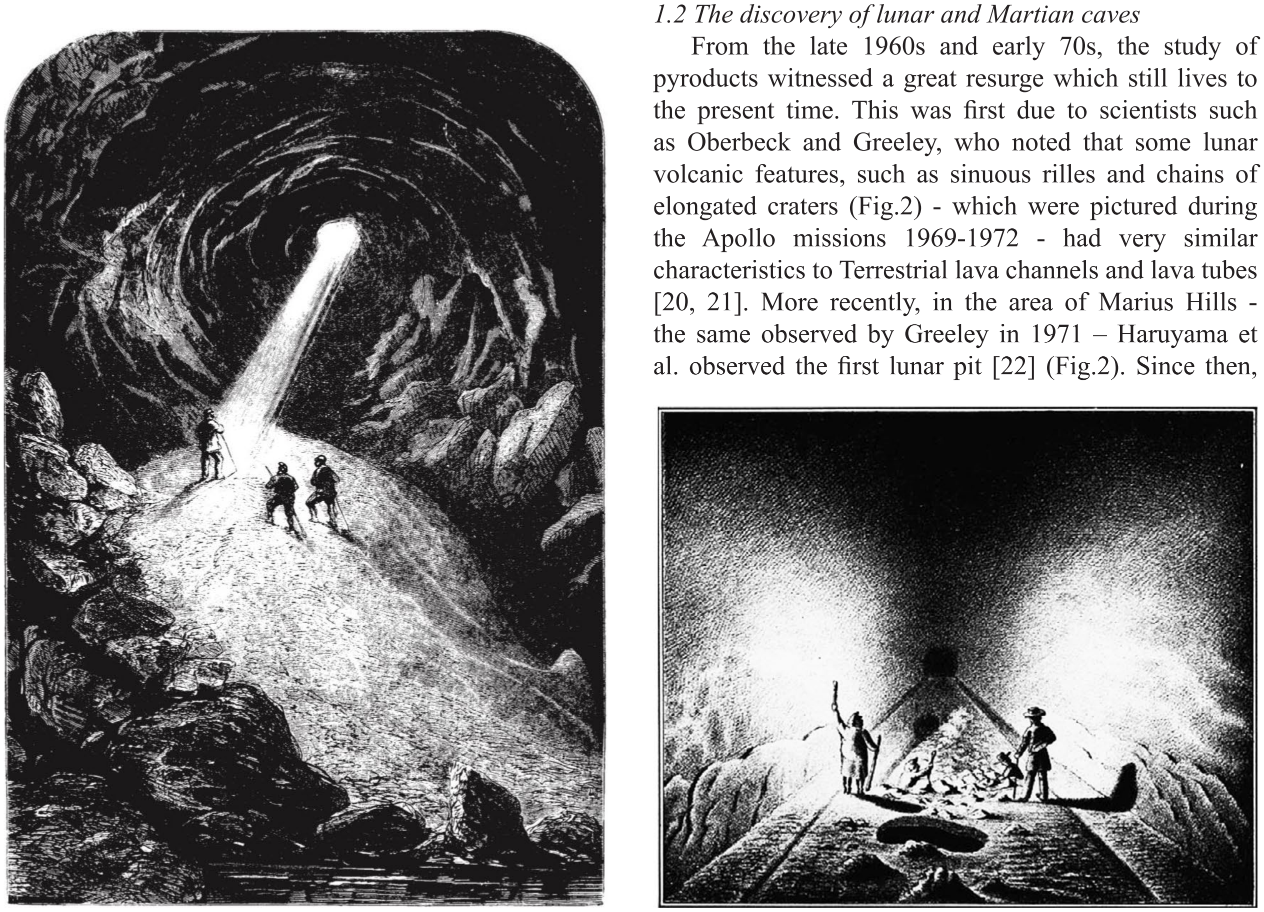

Fig.1 Early illustrations of lava tubes. On the left-hand side, is an 1860 representation of the entrance of the Icelandic lava tube Surtshellir from Forbes [28]; on the right side, is a representation of the Cueva de Los Verdes from Hartung in 1856 [2].

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many new observations have been made, and today 278 pits are known on the lunar surface, possibly indicating the presence of underlying caves [23, 24]. Similarly for Mars, since 2007, more than 1062 cave entrances have been observed, of which at least 349 are potential lava tube skylights [25, 26, 27]. More recently, in 2024, a team of scientists was able to look inside one of the abovementioned lunar pits, located in the region of Mare Tranquillitatis. The study's results indicated strong evidence of the presence of a large underground void, which extends beyond the observed data, making it the most important observation advocating for the presence of lava tubes under the lunar surface [29].

1.3 Lava tubes, ideal sites for future human settlements

As previously anticipated, underground spaces have been widely used by Terrestrial civilizations. Ancient populations used natural caves and artificial excavated spaces to protect themselves from the invaders, the extreme environment and contemporary cities, such as Montreal and Helsinki are still doing so, with extensive underground networks providing both shelter from external conditions or hypothetical conflicts and also thriving urban spaces for the common good [30, 31].

As it is well known, both the lunar and the Martian surfaces are very harsh: extreme thermal fluctuations, radiation exposure, micrometeorite impacts, and dust would significantly impact the health of astronauts and habitat structures in the long run. On the other hand, a settlement located in the underground would be protected from all these hazards. The utilization of the underground in expeditions is nothing new, Roald Amundsen and his team, in the race for the South Pole had built their base with a main outpost on the surface, connected to underground spaces excavated from the crew, where they had additional facilities and were sheltered from the extreme cold and bad weather [32]. For these reasons, many scholars have advocated for locating the lunar and Martian settlements of the future beyond the first exploration endeavors [19, 26, 33, 34, 35].

Because no mission has ever explored lunar or Martian caves, their interior assets remain open to speculation. However, recent studies have inferred that factors such as lesser gravity, rheology of the lava, and higher effusion rates would allow the presence of much bigger conduits than on Earth - with diameters that might reach 40 to 400m for Mars and up to 900-1000m for the Moon, and still be theoretically stable - which is consistent with recent observations [19, 29, 36, 37, 38]. To contribute to the advancement of state-of-the-art extraterrestrial lava tunnel research, in this paper we present "Pyroduct" a new software, developed by the authors, which allows the user to create full parametric 3D models of realistic synthetic lunar and Martian lava tubes, having as ground truth a wide database of Terrestrial data.

2. Material and methods

To develop a full parametric lava tube generator, Rhinoceros's Grasshopper 3D software was chosen. The program is a VPL widely used in the AEC industry and provides users with an intuitive and smart way to handle the complexity of parametric design, both with the use of native and custom components programmable by the user. Also, websites like food4rhino and GitHub are great platforms where users can share their custom

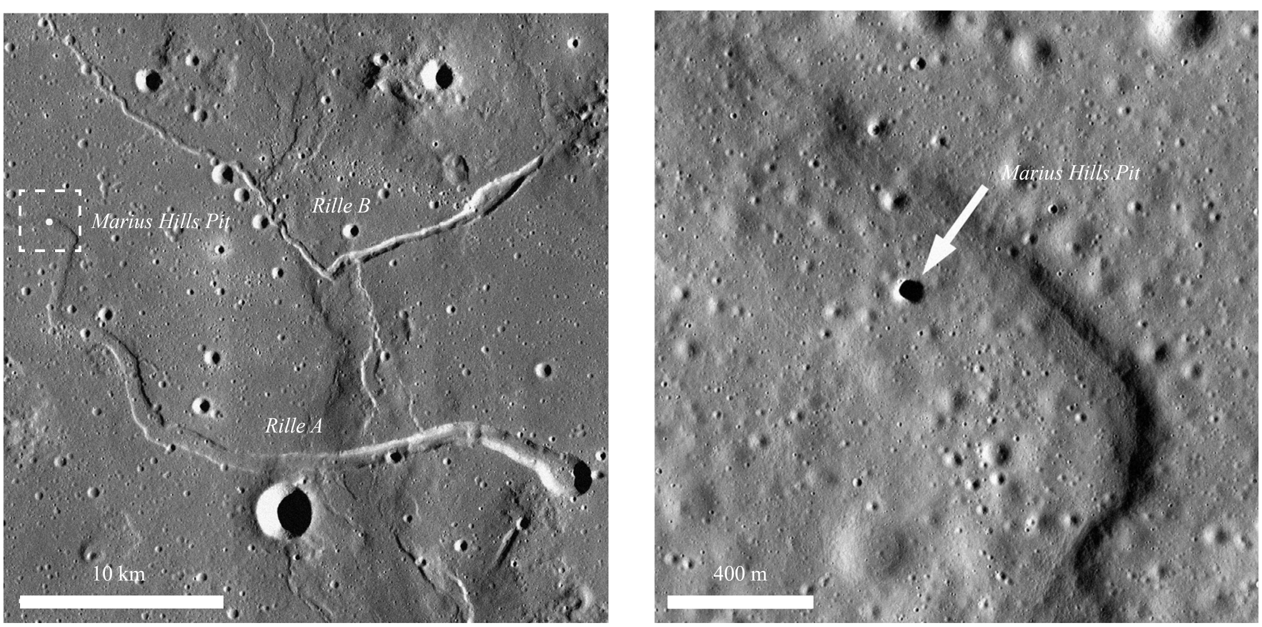

Fig.2 Lunar sinuous rilles. On the left, the Rilles A and B, described by Greeley in 1971 [21] and the location of the Marius Hills Pit; on the right, the Marius Hills Pit, inside the Rille A, first discovered and described by Haruyama et al. [22]. Notice the dimensions of the pit and the ones of the rille.

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components collections to the community – free or not - as easily installable plugins.

2.1 Programming Pyroduct

Pyroduct has been programmed to provide the users with a realistic lava tube generator that allows both complex, very detailed operations and much simpler ones, to develop a useful plugin usable by a wide variety of stakeholders: from scientists to students to architects, engineers, and planners.

To program the software for creating realistic lava tunnels, it was necessary to acquire real terrestrial data, both through the support of a community of experts and on-field expeditions, the last of those on Mt. Etna in June-July 2024, in collaboration with a team of the Department of Geosciences of the University of Padua and with the support of the INGV of Catania.

2.2 The Generation Process

To work, Pyroduct needs RS data of the desired hypothetical observed lava tube that the user aims to generate. Once located the lava tube, the user can proceed with the extraction of the shapefile of the lava tube path and the altimetric data, that can be acquired from the DEMs available for the planetary body which is being observed with the GIS. For Pyroduct to read this data, it is necessary to access it in the Rhinoceros & Grasshopper 3D environment. To do so, it is possible to import the .shp file through the native component of the program or with the use of third-party plugins. Another option is to use the open-source and free software Blender and its intuitive plugin Blender GIS, to save the curve in a .dxf format, which can be easily imported into Rhinoceros and Grasshopper. In addition to the lava tube path, it is also necessary to import the .csv file containing the elevation data extracted from the DEM. Once everything is set, it is possible to proceed in feeding the data into the various Pyroduct components – through the simplified or the complex ones - which guide the user in the creation of a full parametric and synthetic lava tube, allowing full customization and interaction, just by changing the input parameters directly from the Rhinoceros and Grasshopper environments, including the scale, to adapt it to Martian or Lunar dimensions discussed at *1.3*.

At the end of the process, a NURBS surface or a watertight mesh is produced and ready to be used in Rhinoceros or exported to other software for analyses or planning (Fig.3).

3. Results & Discussion

As a result of the process, it is possible to observe in Fig. 3 how, through Pyroduct, diverse and realistic lava tubes are achievable, which can help users and stakeholders in producing credible simulations of how observed Martian and Lunar lava tubes might be, based on the available data and the observations performed. Also, because the process is completely parametric, it allows complete control over the geometry, so that multiple variants of the same lava tunnel can be produced and evaluated, with interesting implications from the scenario planning point of view which are:

3.1 Simulations of extraterrestrial caves

It has been described extensively in *1.2* how the search for extraterrestrial lava tunnels has been going on for a long time. Unfortunately, except for the Apollo 15 mission, which landed next to the Hadley Rille - reported to possibly be a collapsed lava tube - in Mare Ibrium

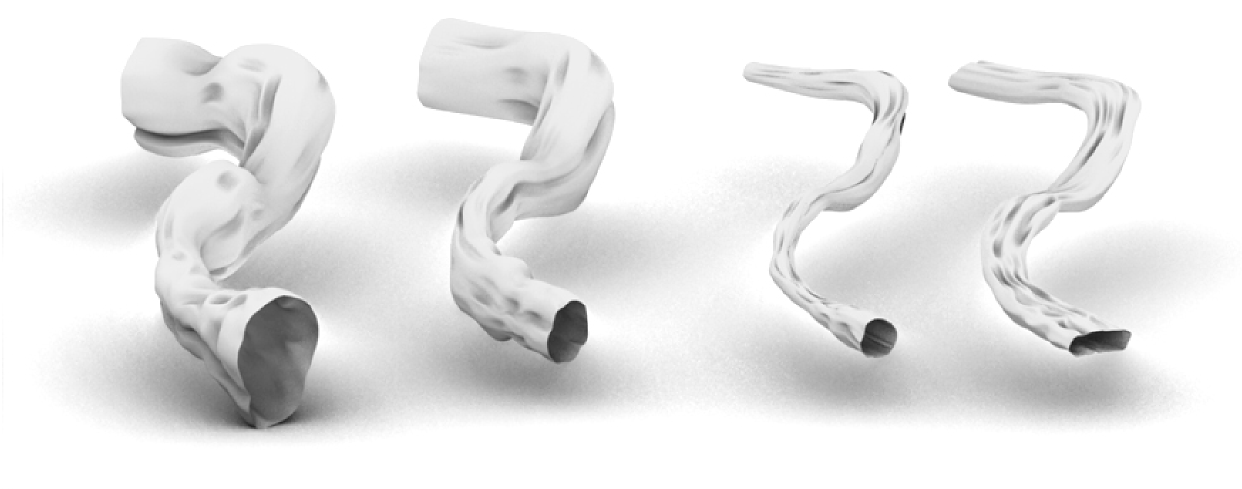

Fig.3 An example of possible usage of Pyroduct. In the picture above, 4 different lava tube meshes were produced, to perform analyses and simulations on the possible shapes and dimensions of a potential lava tube observed on the Moon.

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[21, 33; 39], no other manned or robotic missions have been deployed to approach and investigate potential extraterrestrial caves locations so far.

In recent years, an international community of scientists affiliated with NASA and ESA has developed interesting mission concepts and instruments for exploring the lunar Mare Tranquillitatis Pit and Marius Hills Pit [40, 41]. Even though until a mission visits and scans lunar lava tubes their interiors remain speculative, Pyroduct can assist scientists in exploring and preparing for different possible scenarios that the mission's instruments may face, to foresee potential issues, or to test possible analyses.

3.2 Lava Tubes as ISRU for Future long term human Settlements

Generally excluded from the ISRU framework, except for a few cases [42, 43], pyroducts are terrific resources. As mentioned in *1.3*, lava tunnels can shelter future lunar and Martian settlers from the extreme hazards that characterize the surfaces of both planetary bodies [44]. For this reason, Chinese institutions, such as the NSFC are funding studies for adapting lunar lava tubes for future long-term bases [45].

If compared to the masterplans and designs developed for the surface, until recent times [43, 46, 47] lava tubes have been sporadically considered by the Space Architectural community: in the online bibliography of the site www.spacearchitect.org, a reference for space architects and designers, only 7 papers out of 1419 entries can be found when applying the filter "lava tube" and two if it is used "caves". Nowadays, lava tubes are becoming increasingly interesting for architects and planners, also thanks to international design competitions such as "Moon Station", developed by YAC, with the support of ESA's Topical Team on Planetary Caves [48] and for which the corresponding author developed the prototype of Pyroduct (Fig.4).

In this sense, the use of Pyroduct can provide architects, engineers, and planners with realistic 3D models which test possible habitat solutions and the required logistics to build them, in variable scenarios.

4. Conclusions

This work presents a brief overview of the discovery and study of lava tubes, both on Earth and in extraterrestrial environments, with a focus on the current state of exploration of lunar and Martian caves. From the early observations of lunar sinuous rilles in the 1960s and 70s—thought to be similar to collapsed terrestrial lava tubes—up to the recent identification of hundreds of potential subsurface access points on the Moon and Mars, the field has evolved significantly. Despite numerous observations, no specific missions have yet been deployed to explore these sites directly. However, they represent valuable resources, especially for long-term human settlements and scientific research. For these reasons, there is still no direct data on the internal structure of lunar and Martian lava tubes, despite promising evidence of a significant linear void beneath the Mare Tranquillitatis Pit.

To bridge this gap and support scientists in preparing for future subsurface exploration missions, as well as engineers, architects, and planners in testing scenarios for underground habitats, this research introduces Pyroduct, an innovative parametric tool for generating realistic 3D models of lava tubes. Currently, no other tool offers such a comprehensive and realistic approach

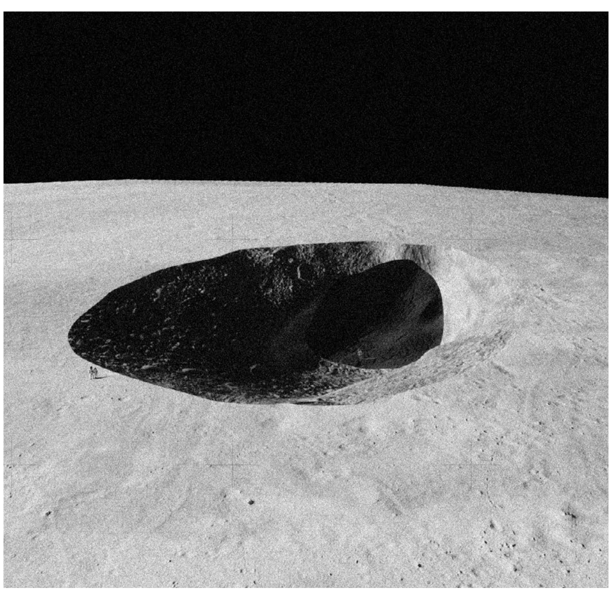


Fig.4 Early applications of Pyroduct: on the left, a render of the Lacus Mortis Pit, with the opening of its possible lava tube on the front wall. The pit was the site of the competition organised by the authors. On the right, the project by Wiktoria Dziadula, Agata Mintus, Paula, Drozdowska et al.

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to lava tube modeling for extraterrestrial environments. This first-of-its-kind software can assist students, professionals, and stakeholders in creating more accurate lava tube simulations for analysis and design purposes. The program is set to be released online in the coming months.

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