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**Additive Construction with Mobile Emplacement (ACME)**

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**Abstract**

Additive Construction with Mobile Emplacement (ACME) is a NASA technology development project that seeks to demonstrate the feasibility of constructing shelters for human crews, and other surface infrastructure, on the Moon or Mars for a future human presence. Additive construction employs the principles of additive manufacturing on a human habitat structure-size scale. The ACME project will allow, for the first time, the 3-dimensional printing of surface structures on planetary bodies using local materials as construction materials, thereby tremendously reducing launch and transportation mass and logistics. Some examples of infrastructure that could be constructed using robotic additive construction methods are landing pads, rocket engine blast protection berms, roads, dust free zones, equipment shelters, habitats and radiation shelters. Potential terrestrial applications include the development of surface structures using Earth-based materials for emergency response, disaster relief, general construction, and housing at all economic levels. This paper will describe the progress made by the NASA ACME project with a focus on prototypes and full scale additive construction demonstrations using both Portland cement concrete and other indigenous material mixtures.

**Keywords:** Additive, Construction, Regolith, Mobile, Resources, Infrastructure.

**Acronyms/Abbreviations**

3 Dimensional (3D) Automated Additive Construction (AAC)  
Additive Construction with Mobile Emplacement (ACME)  
Automated Construction for Expeditionary Structures (ACES)  
Computer Aided Design (CAD)  
Contour Crafting Corporation (CC Corp)  
In-Situ Resource Utilization (ISRU)  
3-Dimensional Printing (3DP)  
University of Southern California (USC)  
United States Army Corps of Engineers (USACE)  
Engineering Research and Development Center (ERDC)  
Ordinary Portland Cement (OPC)  
Key Performance Parameters (KPP)  
Vertical Take-off Vertical Landing (VTVL)  
Materials Delivery System (MDS)  
Dry Goods Delivery System (DGDS)

Liquid Goods Delivery System (LGDS).

**1. Introduction**

While additive manufacturing has recently been the subject of significant research and development advances over the past 20 years, this paper will explain a relatively new type of additive manufacturing technology that has been demonstrated, which is different since it uses indigenous rock aggregates, concrete and mortar type of materials to print large scale structures and civil engineering infrastructure. We create a distinction from other existing additive manufacturing methods by calling this discipline: three dimensional (3D) Automated Additive Construction (AAC) [1], whereby automated construction is enabled by a 3D Computer Aided Design (CAD) model. In addition, the system developed by this team is mobile and can be deployed to the field on Earth which informs future efforts to build a space rated 3DAAC robotic system which could be transported to a planetary

surface, set up and used to construct a base for safe and efficient habitation by an astronaut crew. The name of the prototype developed by this team is “Additive Construction with Mobile Emplacement” (ACME).

The discipline of 3DAAC was first proposed in the 1990’s by Professor Berokh Khoshnevis at the University of Southern California with a method which he called “Contour Crafting” (CC), which is an additive fabrication technology that uses computer control to exploit the superior surface-forming capability of trowelling to create smooth and accurate planar and free-form surfaces [2,3,4]. Further work was done by Prof. Khoshnevis in the 2,000’s under support from the National Science Foundation (NSF) and the National Aeronautics & Space Administration (NASA).

Recently, Dr. Khoshnevis has started a new company to commercialize this technology: Contour Crafting Corporation (CC Corp). Its technologies use specially designed robotic systems to quickly construct buildings using data from 3D CAD designs. While there are numerous applications for these technologies, CC Corp is initially focusing its efforts on transforming and revolutionizing home-building. CC corp. envisions that when CC is fully developed it could enable the building of a house in as little as few hours and at far lower costs than traditional methods. There are more than 100 US and international patents on various aspects of Contour Crafting and other technologies which have been licensed to CC Corp by the University of Southern California and a significant number of additional patent applications are independently in progress at CC Corp.

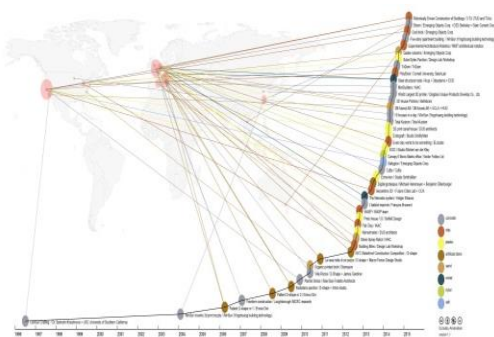


Fig.1. Timeline of AAC projects starting with Contour Crafting at USC in the 1990’s [5]

Other 3DAAC efforts exist internationally as well, with various individuals and entities attempting to prove the feasibility of 3DAAC using a variety of mortar and concrete materials which are mostly proprietary. The 3DAAC industry is still in its infancy, advancing rapidly and very few papers have been published, but interest and activity is high. Bos et al [6] have provided a good summary of the current state of the art.

At NASA there is a high level of interest in using indigenous materials at the space destination (e.g. Moon, Mars) with autonomous 3DAAC robots to construct infrastructure such as landing pads, blast protection berms, roads, hangars, radiation shelters, habitats, antennas, solar power towers and other infrastructure for an astronaut base with permanent occupancy. Using indigenous materials in space is called In-Situ Resource Utilization (ISRU) and by combining this with advanced robotics and autonomy, it will be possible to avoid sending thousands of tons of construction material into space, thereby saving large amounts of money, since the current cost of launching one kg into Low Earth Orbit (LEO) is \$4,000-\$10,000. Launching one kg to the surface of the Moon could range from \$100,000 to \$ 1,200,000. It is envisioned that a small amount of robotic 3DAAC intelligent machines will be sent to the space destination ahead of the astronaut crew arrival. These 3DAAC robots will construct the base (using tele-operations or autonomy methods), so that sustainable infrastructure will allow safe and productive operations to proceed when the crew arrives. This strategy will yield a high mass multiplier effect whereby one kg of 3DAAC equipment launched will avoid 1000’s of kg of construction material launched.

In 2015, NASA partnered with the United States Army Corps of Engineers (USACE), Engineering Research and Development Center (ERDC), Construction Engineering Research Lab (CERL) in Champaign, Illinois to start the three year ACME development project. USACE has similar goals to NASA where there is a desire to rapidly deploy robotic 3DAAC equipment to forward bases to provide cost effective, quality barracks for the troops. In an analogous way to launching 3DAAC equipment into space, USACE will transport the equipment in C-130 cargo transporter aircraft. Both agencies have a need for a modular deployable robotic 3DAAC system. The USACE has a goal of being able to provide 32’ x 16’ x 8.5’ tall B-Huts within 48 hours of the C-130 landing, using locally sourced Portland Cement concrete materials. 3DAAC has the potential to reduce B-Hut building materials shipped by half and reduce construction manpower requirements by 62 percent when compared to existing expedient plywood construction. The use of indigenous materials, combined with advanced robotics on Earth and in space will provide substantial logistics savings and benefits. This project differs from others, since the scale is larger, a variety of concrete materials are being investigated, the speed of 3D printing is higher than previously attempted, the entire system is mobile and fully automated once 3D printing starts, and successive replication of B-huts is possible, in order to build an

entire of set of barracks at one site, quickly and with minimum Army personnel.

## 2. ACME Project

NASA is seeking in-space construction capabilities for deep space mission infrastructure on planetary surfaces. The objective is to build large structures on demand, on planetary surfaces using in-situ regolith to protect landed assets & crews from the local environment (temperature, radiation, vacuum, micro-meteorites, dust, rocket plume ejecta, etc.) ACME uses local regolith materials, advanced robotic positioning methods, and additive manufacturing technologies to achieve 3DAAC in space. This technology directly addresses the NASA Advanced Manufacturing subject matter areas of additive manufacturing, robotics and non-metallic materials processes.

This project has combined technology and expertise from partner organizations to create a leading world-class team. This team demonstrated that 3D printing with concrete is feasible and also investigated alternative materials to Ordinary Portland Cement (OPC) concrete that are indigenous to the Moon or Mars. The lessons learned will be applied to future in-space and terrestrial manufacturing (e.g. USACE Barracks, State of Hawaii Basalt construction) while also leveraging prior technology development efforts, such as Small Business Innovative Research (SBIR), NASA Innovative Advanced Concepts (NIAC), NASA Field Center Investments, etc. It provides risk reduction by providing on demand construction of shelter for robots and crew while significantly reducing launch mass from Earth, (with a goal of zero mass launched after initial equipment has been delivered).

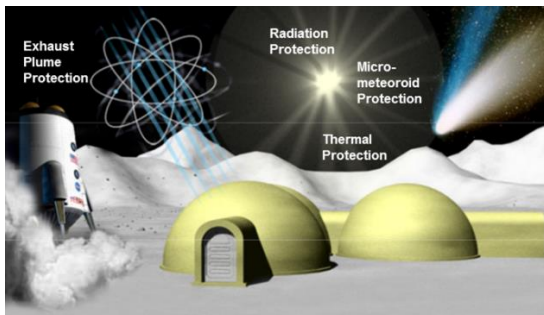


Fig. 2. Shelter from the deep space environment is the top goal for ACME technology development

The ACME team consisted of the following members:

- NASA Marshall Space Flight Center (MSFC)
- NASA Kennedy Space Center (KSC) “Swamp Works”
- USACE ERDC Construction Engineering Research Laboratory (CERL)

- Contour Crafting Corp. (CC Corp.)
- Pacific International Center for Exploration Systems (PISCES)

MSFC and KSC co-led the ACME project and were responsible for all project management.

MSFC was responsible for the additive construction robotic emplacement gantry concept, design and fabrication and testing, materials pumping and delivery, control software, tool path development and concrete materials formulation for Earth and space, including ballistic impact testing.

Contour Crafting Corp. was responsible for the OPC concrete slurry 3D print head concept, design, fabrication and delivery to MSFC as well as consulting related to advanced 3DAAC methods and materials.

KSC was responsible for the robotic excavation of regolith rock aggregates and delivery to a hopper system. In addition KSC provided the concept, design, fabrication, and testing of a Materials Delivery System (MDS) for a custom “on demand” OPC concrete recipe. The MDS consisted of a Dry Goods Delivery System (DGDS) and a Liquid Goods Delivery System (LGDS). In combined operation, these two systems can dispense a precise mixture of dry goods, water and ad-mixtures to create an OPC concrete slurry for pumping to the 3D print head.

PISCES provided a test site and a robotic mobility platform on the Big Island of Hawaii and crushed basalt rock indigenous materials to tele-robotically build a simulated foundation for a habitat which could also serve as a scaled landing pad demonstrator prototype with a 20 meter diameter gravel apron area, and a 3m x 3m “bulls-eye” sintered paver landing site for a vertical take-off vertical landing (VTVL) rocket. KSC provided the requirements and payloads for the mobility platform which consisted of a soil moving blade, a compaction roller and a robotic arm device with a custom gripper for deploying sintered basalt pavers.

MSFC and KSC were jointly responsible for the systems engineering, integration, verification & validation, and overall system performance.

USACE was a partner via shared funding and requirements with their Automated Construction for Expeditionary Structures (ACES) project. By using appropriate project management techniques a joint project was developed where an orthogonal three degree of freedom (X,Y,Z) gantry style robot positioning mechanism was developed and automated with a computer control system which met the needs of USACE ACES and NASA ACME. In the future, it is envisioned that the print head and materials feed system, could be changed from OPC concrete to other material systems such as thermoplastic polymer concretes and other novel cement materials under development.

### 3. ACME Objectives

The USACE had the following objectives for construction of a B-hut in a forward base:

- Reduce construction time from 4-5 days to 1 day per structure
- Reduce construction personnel requirements from 8 to 3 per structure
- Reduced logistics impacts associated with materials shipped, personnel, and resources to sustain the structures and personnel
- Decrease material shipped from out of theater from 5 tons to less than 2.5 tons
- Improved energy performance of the envelope from less than R1 to greater than R15
- Reduced sustainment (logistics) and operations/maintenance personnel
- Reduce construction waste from 1 ton to less than 500 pounds
- Improved security during construction
- Improved local population acceptance by mimicking local construction

NASA had the following objectives for construction of a prototype habitat for feasibility and potential Astronaut crew training:

- First demonstration of additive construction using planetary analog materials
- Provide a detailed analysis of materials for additive construction on different planets, including radiation shielding potential
- Advance the Technology Readiness Level (TRL) of additive construction hardware and processes to provide risk reduction and capabilities to future mission development programs
- Provide the pathfinder to fabricating structures on demand in space with in-situ resources, reducing the need for sizeable structure up-mass
- Provide a significant return on investment by enabling future NASA missions not feasible without the capability to manufacture structures in situ and doing so with significant external leverage
- Provide a first step towards evolving additive construction for use on Deep Space Missions
- Demonstrate tele-operations to reduce testing operations cost and show applicability to planetary surfaces

The Key Performance Parameters (KPP) for the ACME project are listed below in Table 1.

Key Performance Parameters			
Performance Parameter	State of the Art	Threshold Value	Project Goal
KPP-1 Construction Material	Contour crafting with water-based concrete	Use in-situ regolith materials for manufacturing feedstock using imported binders	Use in-situ regolith materials for manufacturing feedstock using no imported feedstock materials
KPP-2 Emplacement	Subscale gantry mechanisms that are fixed in locations	Full scale gantry mechanisms in fixed locations	Mobile-ready print system
KPP-3 Construction Scale	Small concrete dome: ~1m high	In-situ regolith structure pad and curved wall; subscale optimized planetary structure	In-situ regolith structure pad and curved wall; full scale optimized planetary structure
KPP-4 Print Head Construction Speed (1cm thick layers material)	30cm/minute	60cm/minute	100cm/minute

Table 1. ACME Key Performance Parameters (KPP)

### 4. ACME Systems

The ACME system consists of several sub-systems that contribute to an overall work flow that needs to be well timed and choreographed to produce a continuous flow of concrete slurry at the print head for additive construction deposition on the structure being built.

#### 4.1 Foundation / VTVL Pad Tele-operated Robotic Construction

All surface structures depend on a solid foundation that is level and well compacted in order to be load bearing with sufficient margin. It is normal to start with a site survey and then use construction equipment such as tractor dozers to level and grade the foundation. The graded area is then compacted and a concrete slab is poured on it. In some cases pilings are driven into the ground in order to achieve sufficient structural stability.

In order to prove the feasibility of constructing such a foundation using tele-operated robots, a partnership with the PISCES organization in Hilo, Hawaii was formed to explore a pad construction simulation in a local quarry using indigenous crushed basalt rock aggregate as a regolith simulant. The same technology and methods that are needed to robotically construct a foundation can be used to construct a VTVL pad for rocket propulsion descent and ascent vehicles. The blast effects of the rocket plume can cause significant ejecta with velocities up to 2,000 m/s, therefore requiring mitigating steps such as using a VTVL concrete pad. In this case, a simulated VTVL pad with a 20 meter (m) diameter was designed and built. The 3m x 3m “bulls-eye” center area would see repeated rocket engine blasting on a routine basis during launch and landing operations, so it required a strong, durable high temperature resistant material.



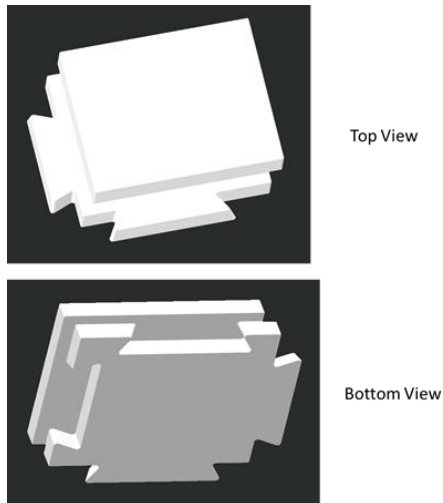


Fig. 3. CAD Views: Interlocking Sintered Basalt Paver for VTVL Pad

Fortunately basalt rock is an excellent high temperature insulator which is well suited for such conditions. NASA KSC Swamp Works and PISCES jointly developed a new sintered basalt interlocking paver that was sintered in a high temperature kiln with indigenous Hawaiian crushed basalt rock used as a feedstock. The material was developed through various design - test - build, cycles until a superior material with an ultimate compressive strength of approximately 30,000 psi was achieved, which is much higher than OPC concrete and also better than exotic high strength Portland Cement specialty concretes.

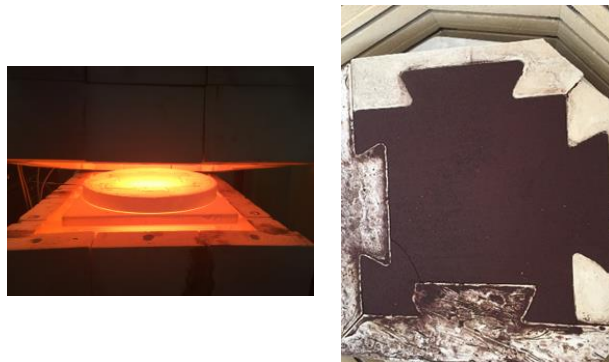


Fig. 4. Left: Basalt Fines Sintering in a mold;  
Right: Resulting Basalt Rock Paver

The quarry site in Hilo, Hawaii was surveyed, and graded, and then the interlocking pavers were installed at the bulls-eye using various payloads on a robotic mobility platform that was tele-operated from the NASA KSC Swamp Works to prove feasibility of remote operations. Internet latencies proved to be cumbersome, so after several pavers were installed with control from the Swamp Works, the rest were

assembled using local tele-operation to accelerate the work flow. The implements shown in figures 5, 6 and 7 below were developed at KSC and installed on the PISCES mobility platform in Hawaii.



Fig. 5. Tele-operated robotic grading operations



Fig. 6 Robotic compaction with a large regolith filled roller



Fig. 7. Laying sintered pavers for the pad bulls-eye

The pad was compacted to a bulk density of 1.8 grams/ cm<sup>3</sup>, with a regolith fines depth of 20-30 cm, and levelled to +/- 3 degrees from the horizontal. The bulls-eye base material consisted of crushed basalt fines < 150µm in particle size over an area of 3m<sup>2</sup>. The

surrounding apron consisted of basalt sand & gravel (area = 90m<sup>3</sup>). In order to avoid lofting of the sand by a rocket plume impingement, the sand was covered with apron stabilizer: 21 m<sup>3</sup> of #3B Gravel (5 cm deep). All operations were demonstrated to be feasible with robotic means.



Fig. 8. Bulls-eye pad: 100 sintered basalt pavers

#### 4.2 Regolith Aggregate Excavation

In order to create an indigenous concrete construction material in space, aggregate must be excavated from the local site. The ACME project leveraged from previous work done at the KSC Swamp Works called the Regolith Advanced Surface Systems Operations Robot (RASSOR). This design can handle low gravity environments due to its novel counter-rotating bucket drums excavation implements. The horizontal digging forces cancel each other out while the vertical reaction forces are cancelled by the curved self-anchoring scoops which pull down as they dig. The KSC Swamp Works was awarded a United States patent # US 9,027,265 B1 for this design and a prototype was built and tested, which weighs 60 kg and can excavate and carry 80 kg of regolith in the 2 bucket drums per load. This robot is ideal for scooping granular material off the surface for use as feedstock on planetary surfaces.

#### 4.3 Aggregate Delivery

The regolith aggregate that is excavated must be delivered to the ACME 3D printer. In space it is envisioned that RASSOR can deliver it to a lift hopper which can then supply the materials delivery system.

For the ACES version of the 3DAAC system, a Multi-Terrain Loader (MTL) was used to transport and load the aggregate into the DGDS hoppers. It has the advantage of being able to efficiently scoop, lift and dump aggregate through a split bottom bucket. A typical MTL is shown in Figure 10.



Fig. 9. RASSOR 2.0 being tele-operated in a test bed



Fig. 10. Multi Terrain Loader used to deliver Aggregate

#### 4.4 Materials Delivery System

The materials required to make a concrete slurry material must be delivered to the concrete mixing system. In the case of the ACES/ACME 3 system, 7 different dry goods such as Portland Cement, 3/8 inch gravel, coarse sand and fine sand as well as other specialty additives must be metered and delivered in accurate doses to make a concrete mixture with suitable properties for 3D printing via FDM nozzle extrusion. These dry goods must be mixed with water and 3 other liquid admixtures to produce the final concrete slurry which has a suitable rheology for reliable 3DAAC. The MDS is a fully automated system that can supply the ingredients for any desired concrete mix recipe that is entered on a user interface touch screen. The MDS must batch supply adequate concrete to the “Scoop-N-Mix” implement which is mounted on the MTL to batch feed



a concrete pump mounted on the ACES/ACME gantry mechanism.

#### 4.4.1 Dry Goods Delivery System

The DGDS is a custom design which can store and accurately dispense seven different dry goods from steel hoppers via an automated computer controlled auger feed system. The dry goods are dispensed into a separate weigh hopper that is mounted on four load cells that inform the control system and operator of the dispensed dry goods mass. The design was driven by the requirement to be capable of delivering one cubic yard of concrete per hour to the ACES/ACME 3D printer and the requirement of being able to package it on a 10' x 20' shipping pallet that can be loaded onto a C-130 aircraft or USACE flat rack truck for transportation.



Fig. 11. Dry goods in weigh hopper



Fig. 12. Dry Goods Delivery System (DGDS)

#### 4.4.2 Liquid Goods Delivery System

The LGDS is designed to automatically dispense water and 3 other admixtures to the dry goods mix. It has calibrated flow meters that measure the amount of each liquid as they are pumped out of a set of nozzles mounted at the “Scoop n Mix” interface, where it is added to the mixer as the dry goods are also dispensed.

The LGDS is integrated into the DGDS structural frame and control system.

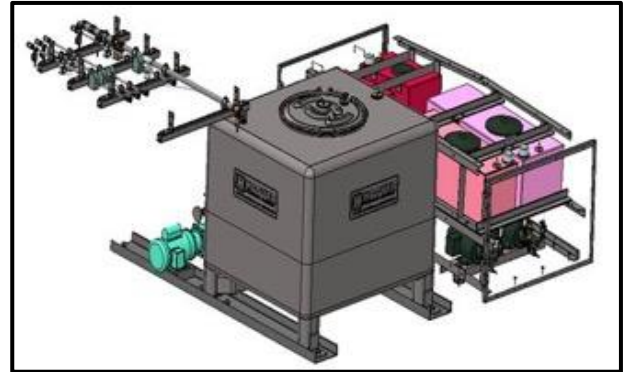


Fig. 13. Liquid Goods Delivery System (LGDS)

#### 4.5 Additive Construction Robotic Emplacement Gantry System

The ACES-3 additive construction gantry system was designed to meet the NASA and USACE objectives requirements discussed earlier. This included meeting the requirements of operating in a humid environment, using in-situ materials, meet mobility requirements and meet the accuracy and build time requirements. The gantry system was sized to autonomously manufacture a 32 ft. by 16 ft. structure that is up to 10 ft. tall in time frame of 24 hours with stringent positioning control of the print head. The structure was also designed to be transported on a C130 aircraft. The major subsystems of the additive construction system include the pump and accumulator on a trolley, two trolleys with towers on each, bridge located between towers, carriage that moves along bridge that contains an extendable boom, slip ring and nozzle, automated levelling system, electrical systems including control box, transformer, Ground Fault Circuit Interrupter (GFCI), cabling/connectors and a rail system.

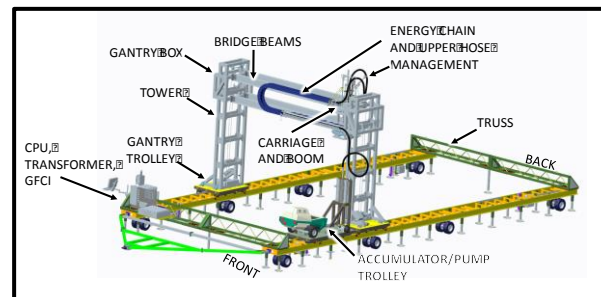


Fig. 14. Design model of ACES-3 automated additive construction system

The pump and accumulator were placed on a trolley that follows the gantry trolleys so the hose length could be shortened. The concrete is delivered to the pump from the “Scoop-N-Mix” system and pumped through

the accumulator to the nozzle attached to the boom and located on the carriage. The function of the accumulator is to allow the concrete to build up when flow is stopped at the nozzle to allow for construction of doors or windows without shutting off the pump. The system has three degrees of freedom, one in the x-axis moving along the rail, one in the y-axis moving along the bridge and one in the z-axis along the tower. The nozzle has rotational capability as well as trowels for shaping. The system can move the nozzle at a maximum speed of 8 inches/sec. The system can be coarse levelled using the automated levelling jack system and precise levelled using a laser level and fine levelling of the support legs. The overall system was designed to be disassembled into small segments and shipped.

The ACES-3 system was shipped from NASA MSFC located in Huntsville, Alabama to the USACE CERL located in Champaign, Illinois. The system was assembled and then moved over a pre-poured concrete pad to perform an additive construction demonstration that will occur later this year. A prototype version of the gantry system, ACES -2 was used to build the first B-Hut which lacked precision and was not mobile. ACES-3 is designed to be transportable, mobile and precise with an advanced trowelling print head provided by Contour Crafting Corp.



Fig. 15 ACES-3 Additive Construction System

## 5. Results and Discussion

The ACME KPP relate to a Fused Deposition Manufacturing (FDM) type of 3D printing with a concrete or mortar material slurry. The binders varied as multiple materials are under study for planetary construction materials, including sulphur, various thermoplastic polymers, sintered and melted basalt, and cementitious materials [e.g. 7,8,9,10,11,12]. Under the ACME project, sintering, thermoplastic polymer extrusion, and cementitious materials have been explored. The USACE prefers to use OPC as a binder since it can be locally sourced almost anywhere in the world. The current mixture used in the second-generation ACME additive construction system

(ACME-2) at MSFC is composed of OPC, stucco mix, water, and a rheology control admixture. A mixture containing primarily the standard mixture but also containing the Martian regolith simulant JSC Mars-1A has also been printed at MSFC, at terrestrial ambient conditions [13]. KPP-1 (In-situ regolith materials feedstocks) was successfully met with several different material systems.

A mobile gantry 3D printing system was developed and tested. It is capable of being packaged into modules that can fit and be transported on a C-130 aircraft. When fully assembled it can be moved from one B-Hut foundation pad to the next with a self-levelling jacking capability. KPP-2 (Mobile-ready print system) was successfully met with the ACES/ACME 3 gantry emplacement system.

The ACES/ACME 3D AAC system, is capable of constructing a full Army B-Hut with a rectangular 512 ft<sup>2</sup> footprint and 8.5' high walls. Currently the roof structure is separately built and assembled. KPP-3 (Construction Scale) was met by using a concrete B-Hut as an analog for a planetary structure. The same method could be used with different indigenous materials, depending on the space destination site.

In the ACME/ACES 3D AAC system, an OPC concrete slurry with 3/8 inch gravel aggregate, sand and other dry goods is being used. It has been successfully demonstrated that it is possible to print at 10 inches per second at full speed, with a material slurry bead that is ~1" high by ~1 1/2" wide. This results in a volumetric material printing speed of 15 in<sup>3</sup>/second or 900 in<sup>3</sup>/minute. (14,748 cm<sup>3</sup> per minute). The KPP of 100 cm<sup>3</sup>/minute corresponds to ~ 381 cm<sup>3</sup> per minute which is ~23.3 in<sup>3</sup>/minute (assuming a bead section of 1 cm x 3.81 cm). The results achieved by the ACME/ACES 3 prototype have far exceeded the KPP set at the outset of this project. *The current print speed is ~39 times faster than KPP-4 (print head construction speed) goal.*

Based on the ACME KPP results, the project has met and exceeded expectations. Further work is necessary to raise the TRL for space, but this is a very promising first step in the NASA quest to build a permanent base on another planetary surface. By using advanced technology and indigenous materials it is highly likely that a sustainable and feasible method of 3D AAC for building infrastructure is realistic.





Fig. 16. Completed ACES-2 3D Printed B-Hut

The objectives of this project were ambitious and it was not clear at the outset if they could be achieved or if the KPP could be met. By constructing a prototype and using various concrete material formulations, it has been established that 3DAAC is a viable method of construction with a high potential for enabling rapid and sustainable construction on Earth and in space. The

This should explore the significance of the results of the work, not repeat them. A combined Results and Discussion section is often appropriate. Avoid extensive citations and discussion of published literature.

## 6. Conclusions

The objectives of this project to rapidly deploy 3DAAC equipment and 3D print a large scale “B-hut” habitat within 24 hours using OPC concrete materials were ambitious and it was not clear at the outset if they could be achieved or if the KPP could be met. This team demonstrated that a foundation made of Hawaiian regolith simulant basalt materials could be robotically constructed via tele-operation. By constructing a prototype 3DAAC system, and using various concrete material formulations, it has been established that 3DAAC is a viable method of construction with a high potential for enabling rapid and sustainable construction on Earth and in space. The robotic gantry and MDS that were developed and used are deployable on a C130 aircraft, so that the system can be transported worldwide. Local indigenous materials can be used for the concrete so that a substantial savings in logistics transportation can be achieved. Manpower can be reduced and the resulting B-Hut has structural and insulation properties that are far superior to the current USACE plywood construction methods.

In space the same type of methods can be used, using more advanced autonomous robotics and indigenous concrete materials that are locally mined and processed. The savings in transportation mass will amount to thousands of tons of construction material for surface infrastructure in a future human occupied base.

New types of habitat architectural designs will be possible. In addition the resulting self-sufficiency and sustainability will enable the pioneering of the space frontier by a new human civilization.

## Acknowledgements

The ACME team would like to thank the NASA Space Technology Mission Directorate (STMD), Game Changing Division (GCD) for funding this project and providing excellent program management. It is hoped that this work can be the catalyst for future technology development work with eventual deployment on a planetary surface to construct infrastructure using indigenous resources.

Our collaboration with the USACE CERL has been highly valued with significant exchange of expertise and joint requirements. The leveraged funding was a model for collaboration between two federal government agencies with mutual benefit and tangible results in the form of prototype hardware that can be evaluated and tested by the users.

The state of Hawaii provided matching funds for this project via PISCES support and it is hoped that this technology can be used in Hawaii with indigenous materials to benefit the local citizens and their economy.

Dr. Berokh Khoshnevis provided invaluable insight into concrete and mortar slurry 3D printing and years of experience which allowed the ACME team to address and solve many issues in this new technology area.

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