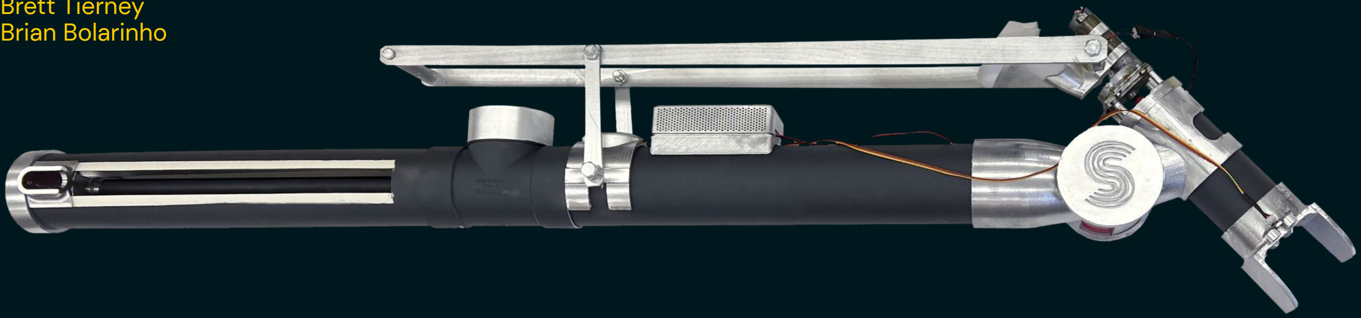
SPACIOUS

Dan Rapoport

Supported by
Brett Tierney
Brian Bolarinho



Making Space for Everyone.

PROJECT TEAM

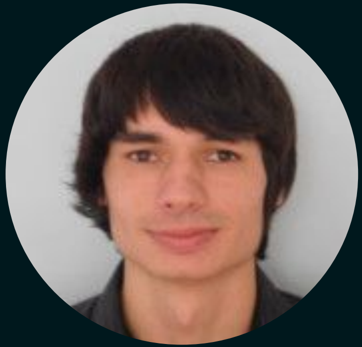
Dan Rapoport
Project Lead

Architect,
Design Engineer

Supported by

Brian Bolarinho

Biomedical
Engineer ScM.



Brett Tierney

Biomedical
Engineer ScM.

Since early 2020,

construction costs have **risen 31%** and over

1.2 million (16%) construction workers left the industry*

*US Census Bureau

This has **increased adoption of 3D Construction Printers (3DCP)** within the industry and beyond

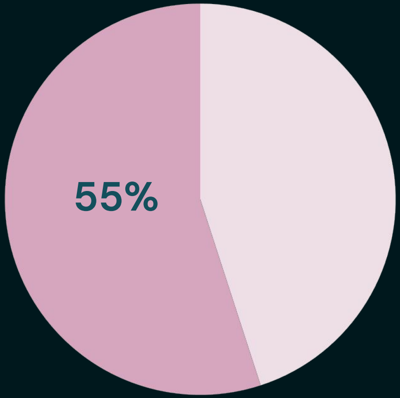
ICON3D, USA

COBOD, Denmark, Malawi

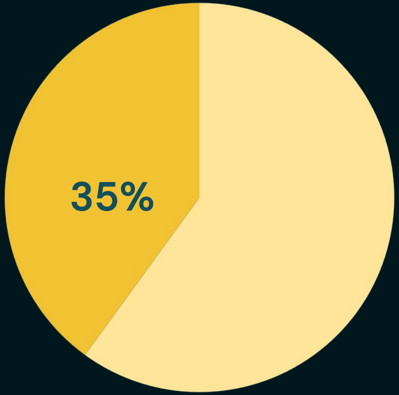
WASP, Italy

RISE OF THE MACHINES?

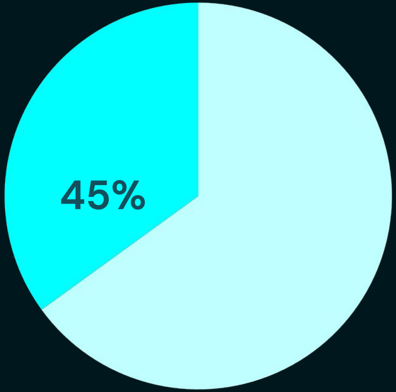
Claimed Cost Savings



Claimed Labor Savings



Claimed Time Savings



Hossain MA, Zhumabekova A, Paul SC, Kim JR. A Review of 3D Printing in Construction and its Impact on the Labor Market. *Sustainability*. 2020; 12(20):8492. https://doi.org/10.3390/su12208492

HOWEVER...

"I've literally talked to people who said, "we didn't include the labor to operate the printer because we expect that to be automated in the future."

All of the people quoting costs right now have a huge incentive to underestimate".

–Louis Vaught,
Materials Production Engineer,
ATSP Innovations

3D CONSTRUCTION PRINTING

3D Construction Printers (3DCP) are very precise, but they still suffer from

- Long setup times
- Large machinery size
- Complex Interfaces
- Operator specialization
- Limitations in print area

COBOD Gantry System

SOMETHING BETTER

If 3D printing could overcome these issues, it could be more than a novelty

3DCP could democratize building by lowering construction costs and simplifying logistics considerably.

Build faster, better, more complex

PERI (Germany)

LET'S FIX IT!

FIXING 3DCP

Create a tool with similar print accuracy that is:

Quick to set up

Mobile

Easy to control

Works independently

Infinitely scalable

LET'S TALK

Concept

Neri Oxman
General Polymath
Founder, Oxman

Michael Lye
Space Design Expert,
RISD Professor

Rick Fleeter
Brown Professor of
Space Engineering

Gui Trotti
Space Architect,
Space Suit Designer

John Vickers
Principal
Technologist
NASA STMD

Andy Law
RISD Professor
Industrial Design

Implementation

Jeremy Philamon
MADE Student
IoT Expert

Eric Rosen
Brown PhD, C.S.
Kinematics Expert

Hongyu Li
MADE Student
Unity Expert

Kennedy Lui
RISD ID Student,
3D Printing Expert

Elliot Laidlaw
Brown Student, C.S.
Computer Vision

Ben Jurgensen
RISD Professor
Sculpture &
Mechatronics

GOAL

Design a better 3D Construction Printer for mass adoption by the industry; **smaller, positionally-aware, with a simple visual interface.**

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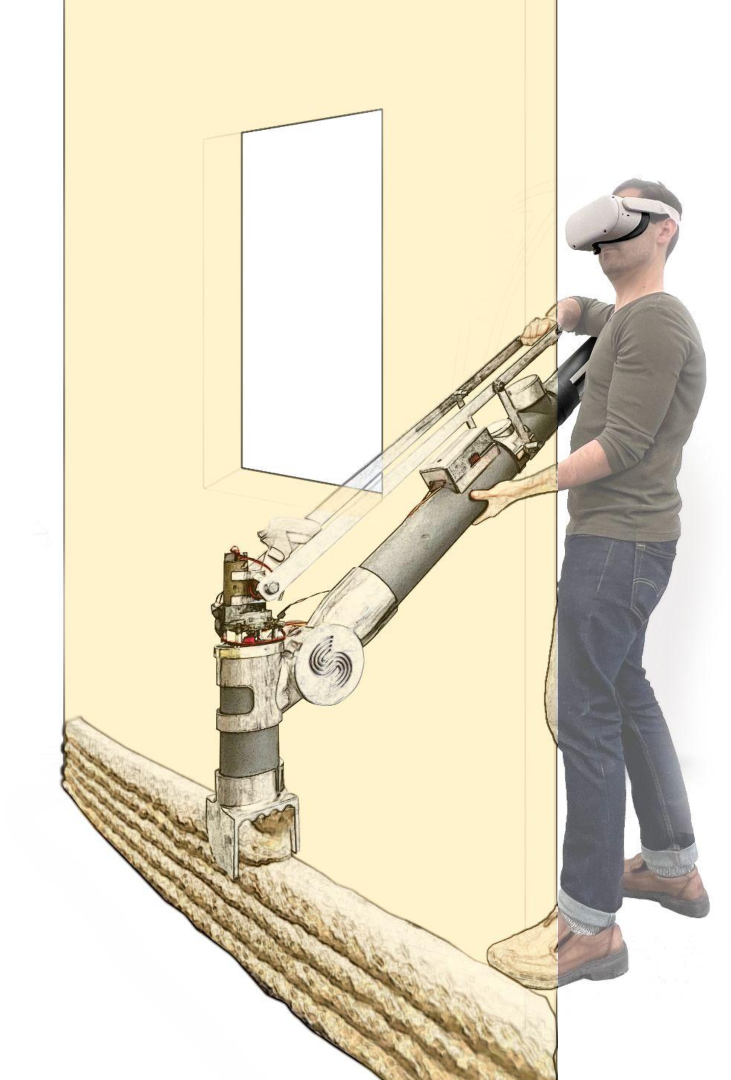
Design a better 3D Construction Printer for mass adoption by the industry; **smaller, positionally-aware, with a simple visual interface.**

Easy, right?



PROTOTYPING

PHASE 1

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Device
Materials
Control System
Augur half Scale Test
Augur Test Full Scale
Thick walls low volume
Thin walls, high volume
Thin walls plus pug mill head
Motor test Full scale
NEMA 17 Stepper Low torque, high control
12V DC Drill Motor low torque
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Body Integration
Extruder Full Redesign
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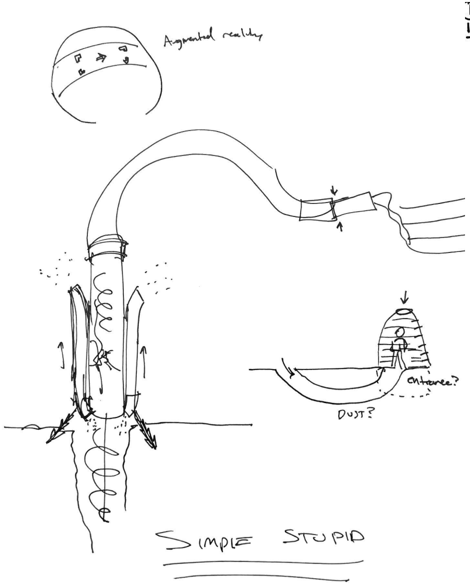
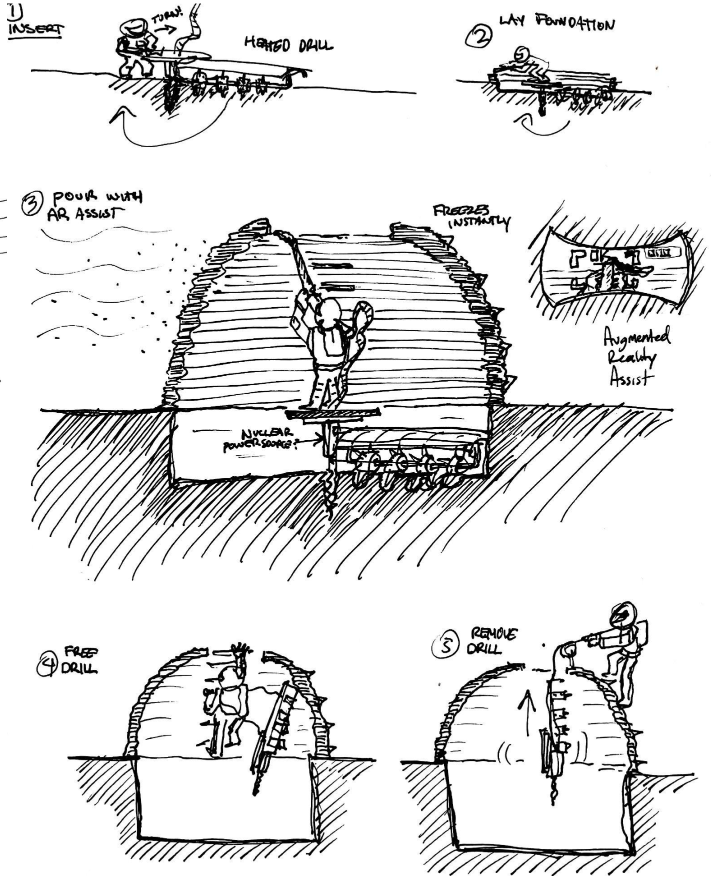
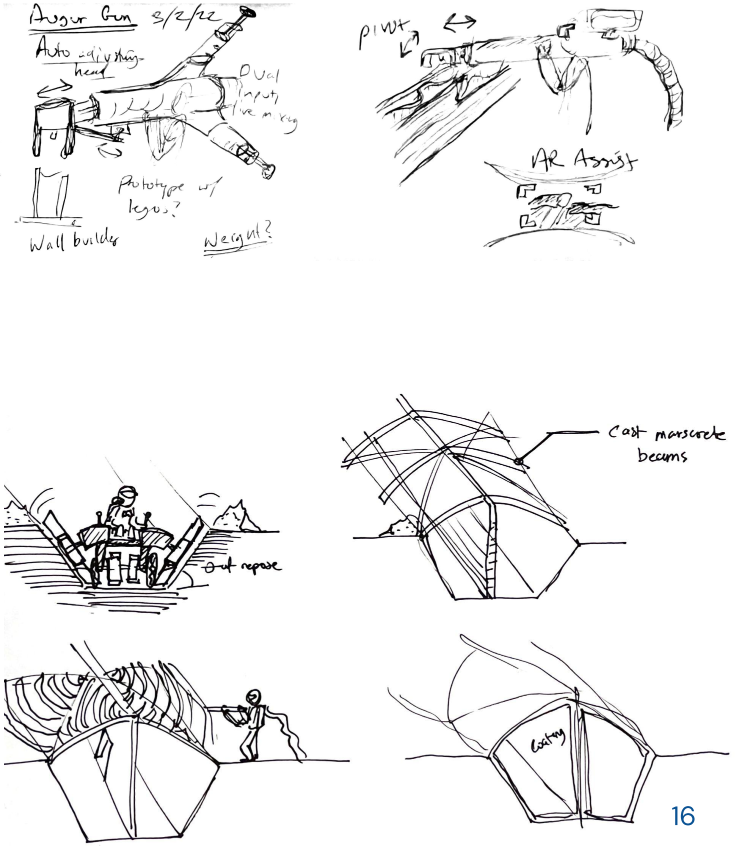
WHERE WE LEFT OFF...





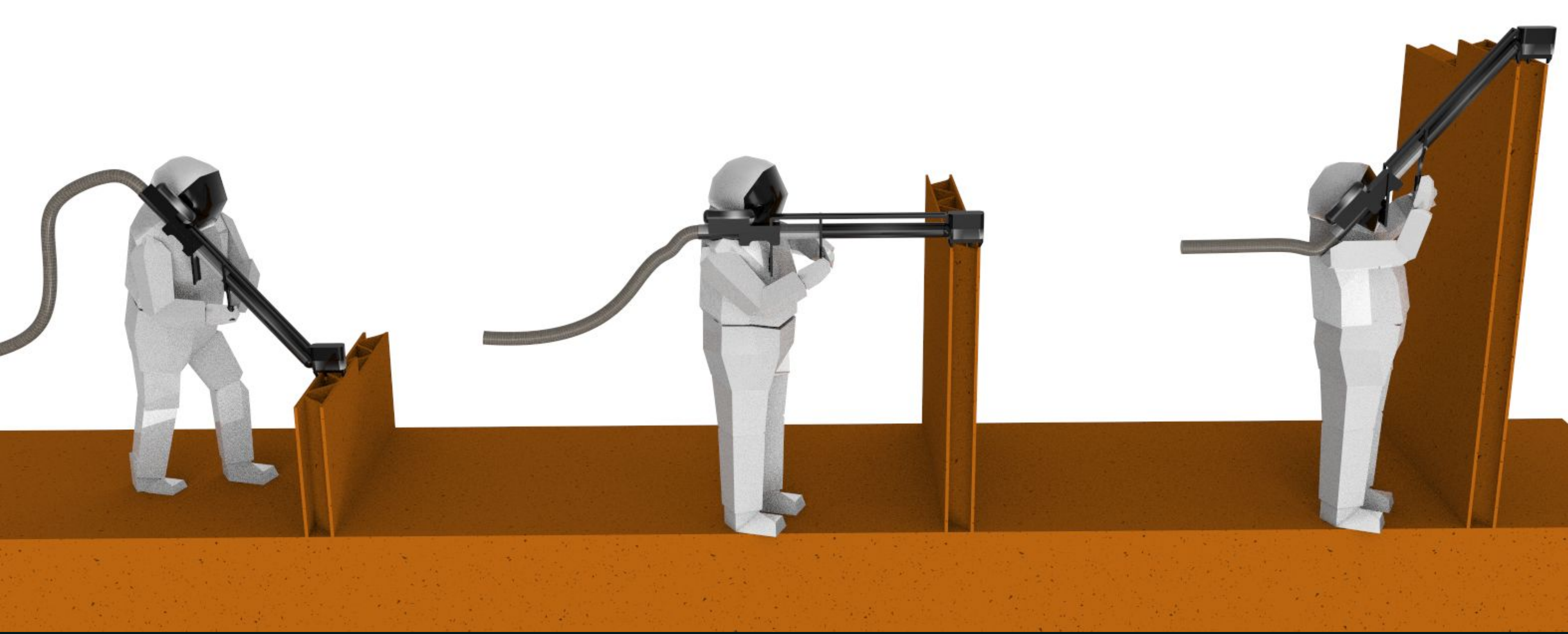


Keep it simple.

Go underground.

Keep humans in the mix.

CONCEPT



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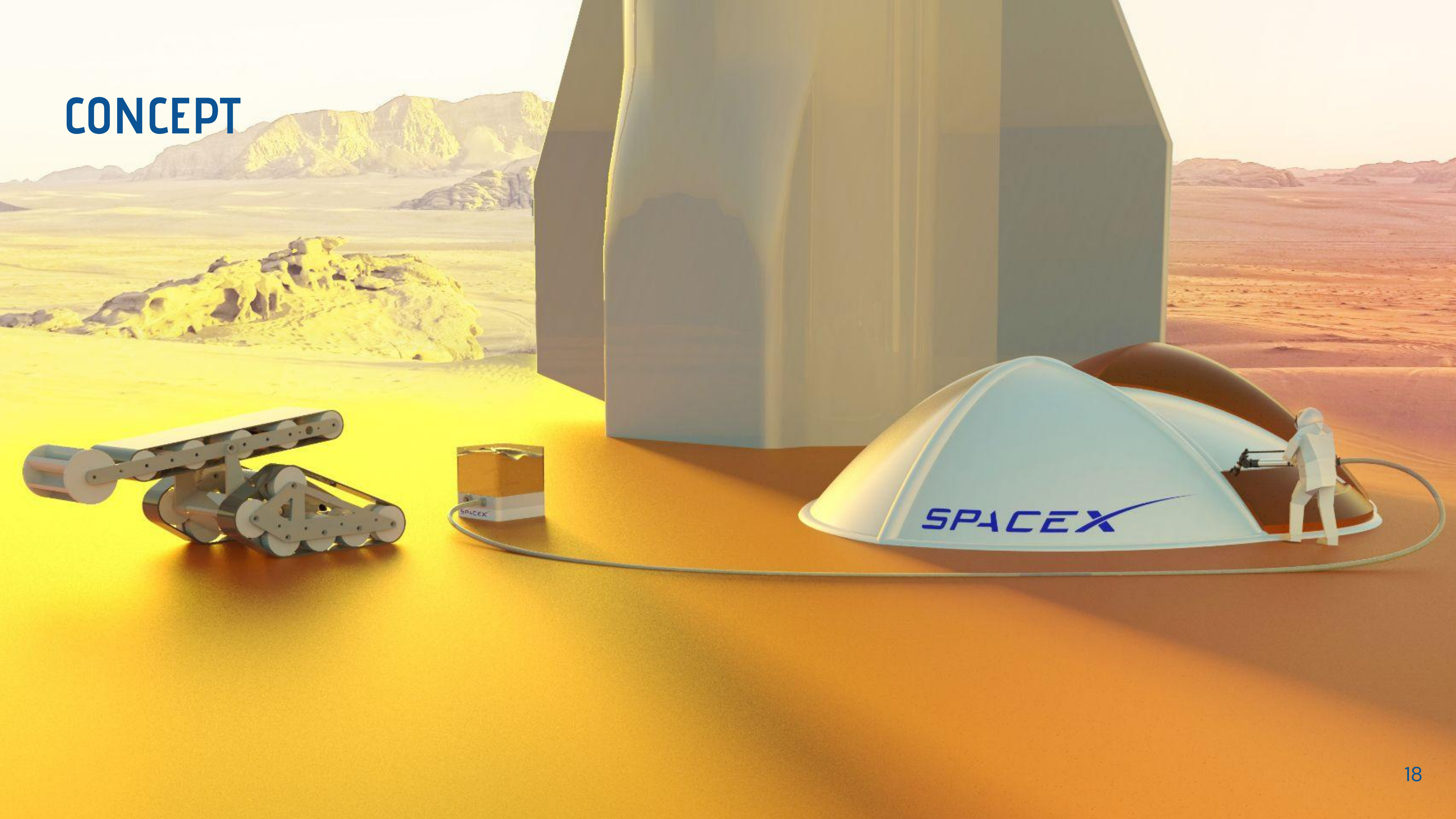

"Perhaps we should get it to work on Earth first".

Michael Donohue
Program Director, Masters of Science in Technology Leadership, Brown University

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WEIGHT AND MOBILITY

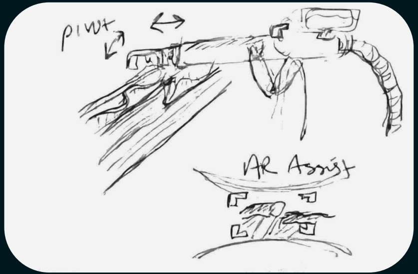
"The current space suit has the mobility of your average 85-year old man. You'll need to design for that".

Michael Lye
Space Designer,
RISD Professor

WEIGHT AND MOBILITY

Challenge:

Develop a tool that one person can easily hold and manipulate



Generative Sketch

Two point connection

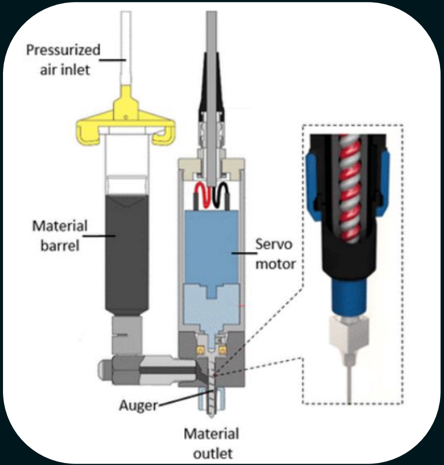
Adjustable angle

EXTRUSION

Handheld extruders are **commonly used for plastic welding**.

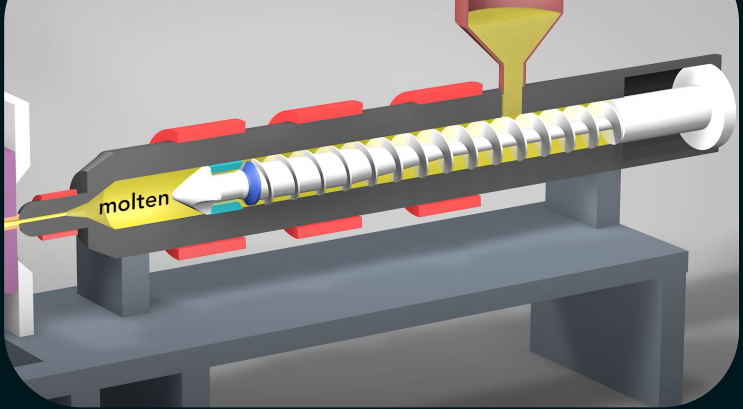
Ceramic/concrete extrusion heads are utilized in 3D printing.

Can we combine them to use the minimal amount of machinery?



Clay extruder head

Plastic mold injector



Plastic Welding gun

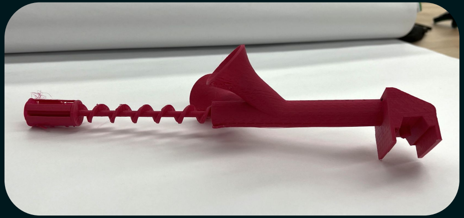
EXTRUSION

Challenge:

Develop
Extrudable materials

Develop a device to extrude from

Proof of concept extruder



Half-scale Extruder Head

PROTO 1 TEST

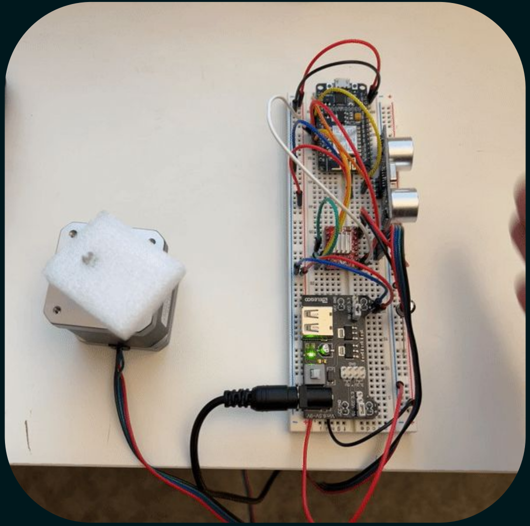
Fly ash cement, sifted from portland cement:

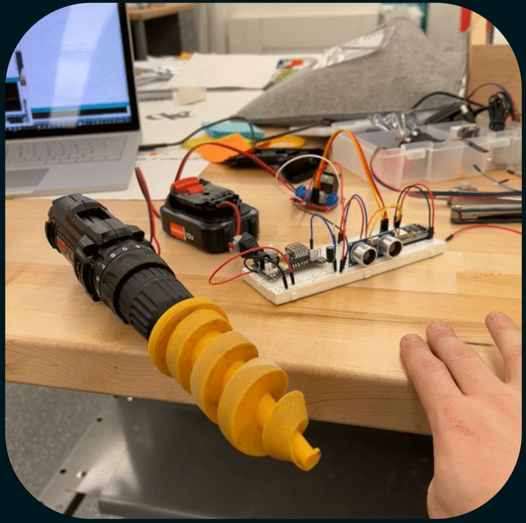
Brittle, but extrudable

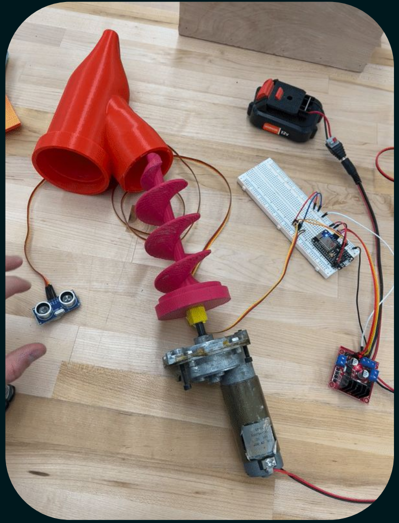
Custom Sifter, Acrylic

TORQUE

Tested many motors to **find the correct torque** for concrete extrusion

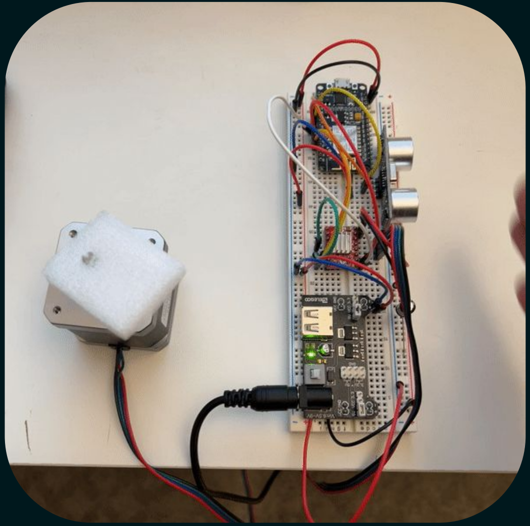


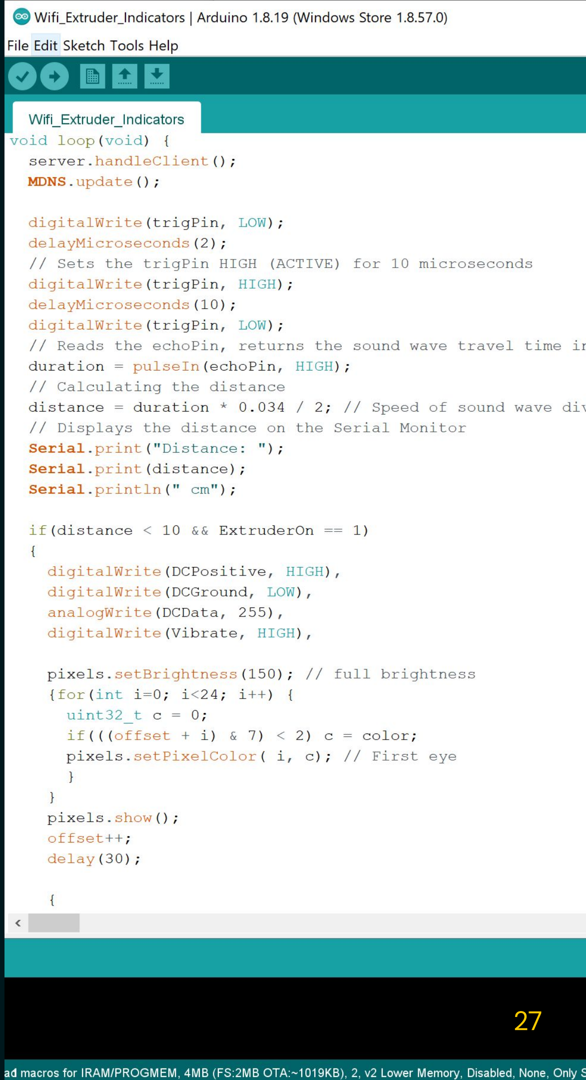




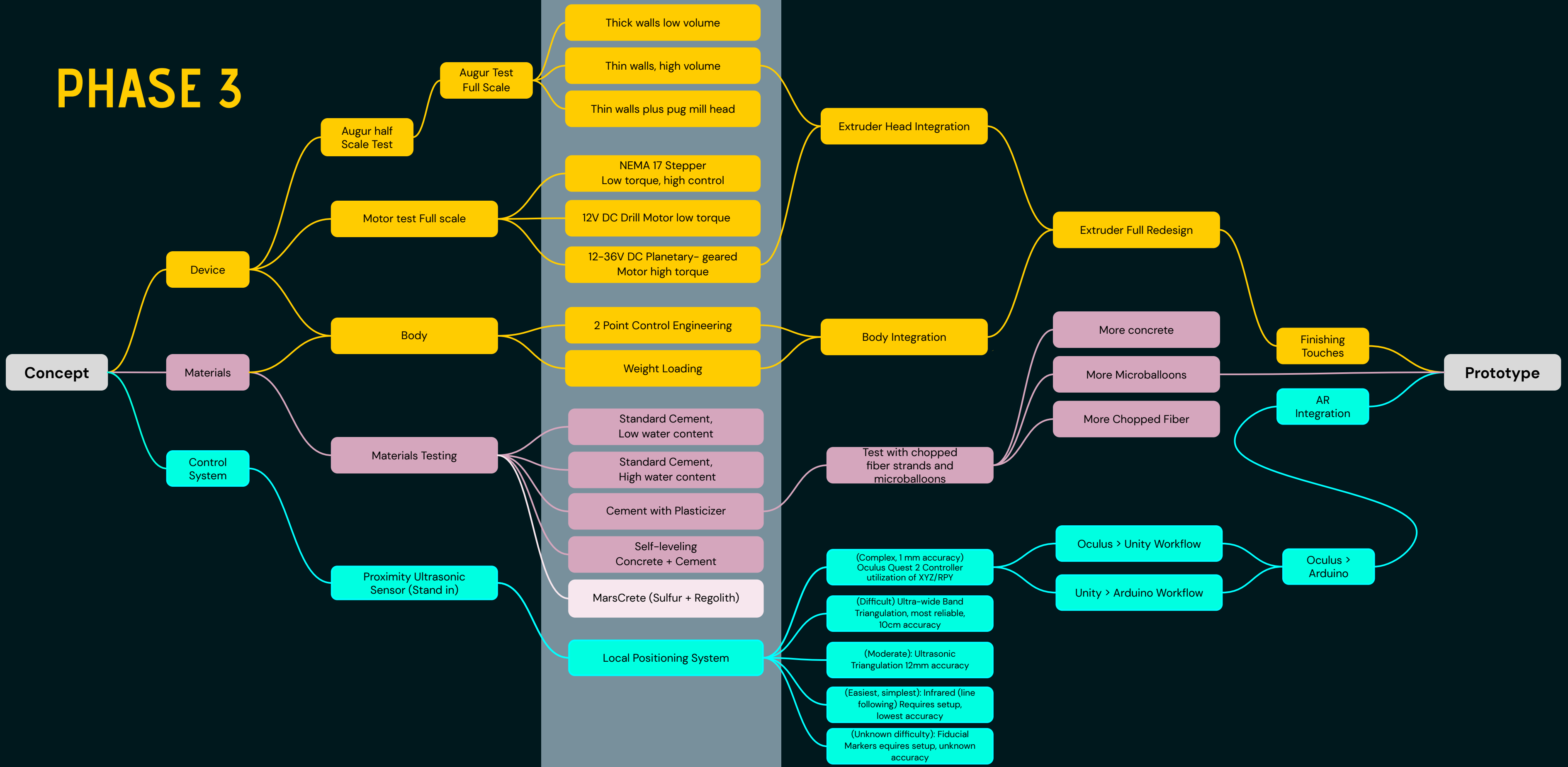
CONTROL SYSTEM

I started with an **ultrasonic proximity sensor** to stand in for positional data and wrote C++ code





PHASE 3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EXTRUSION

Developed an extrusion head with a **narrow profile for linear deposit**

Developed pug-mill inspired augers to **break up large chunks** of material

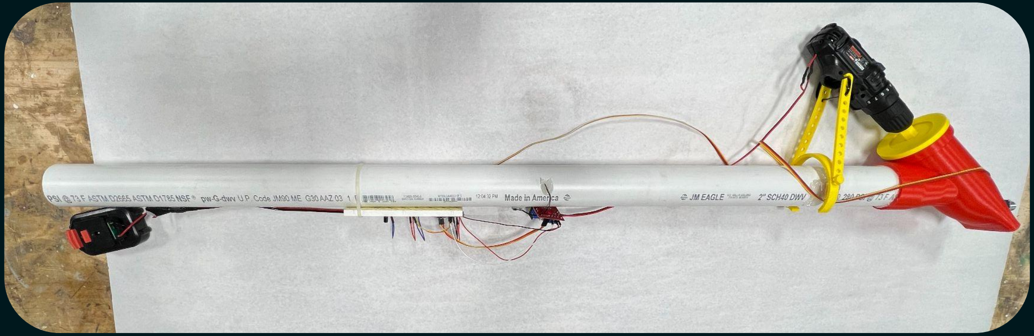
Tested different pitches and thicknesses of Auger

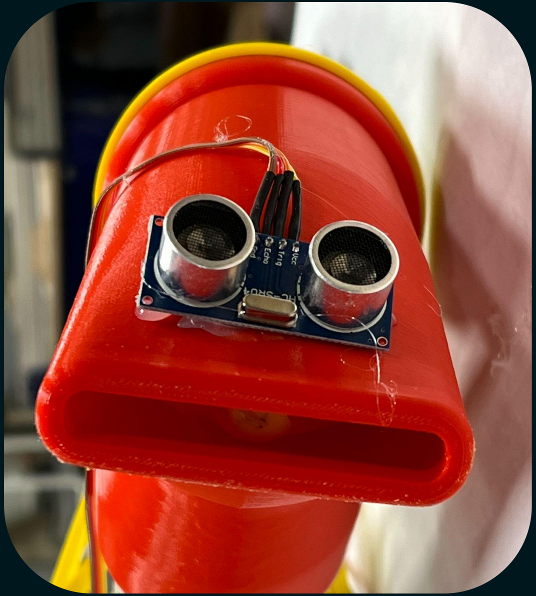
Pug Mill (clay pump)

PROTO 2 TEST 1

First combined control system and extrusion test.

Failure: Mix too viscous, stuck in body





PROTO 2 TEST 2

Failure (left)
Success (right)
with high torque motor

MATERIALS

Winning mixture:

(35%) Fly Ash

(35%) Microballoons

(<1%) Plasticizer

(<1%) Chopped Fiber

(30%) Water

DETOUR: MARSCRETE

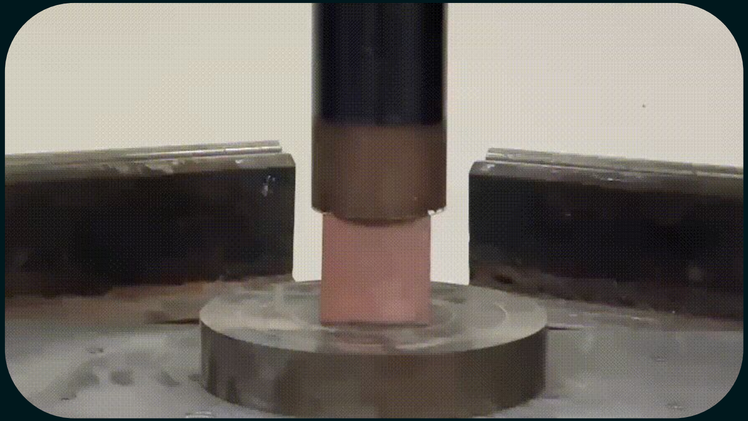
Heat Martian Regolith and Sulfur @150C

Produces a concrete-like material without any water

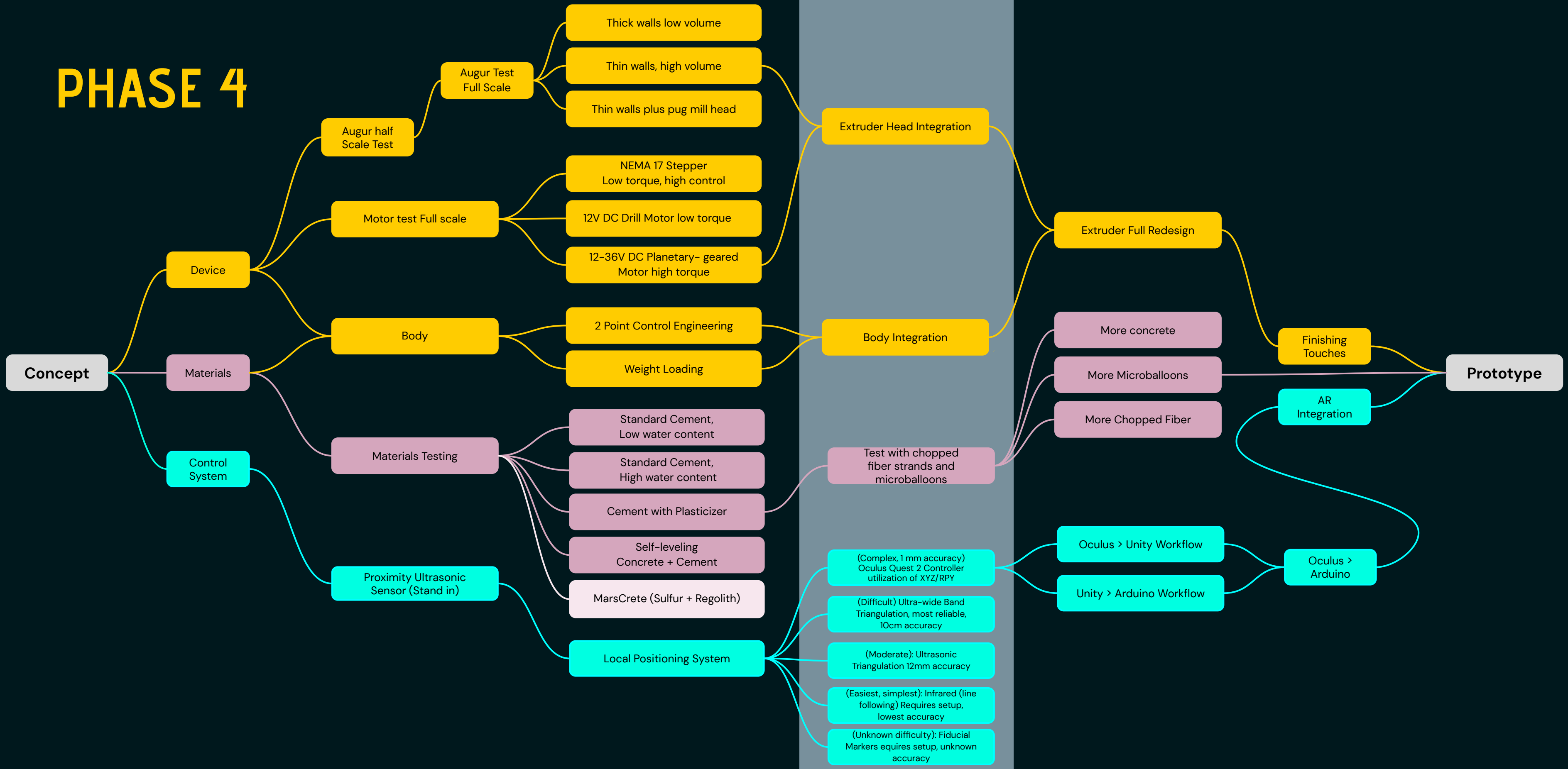
Compressive strength of around 50 MPa (Normal concrete is 17-28 MPa)

Add a dash of polyethylene (1%), becomes a great radiation barrier

Easy to Make



PHASE 4



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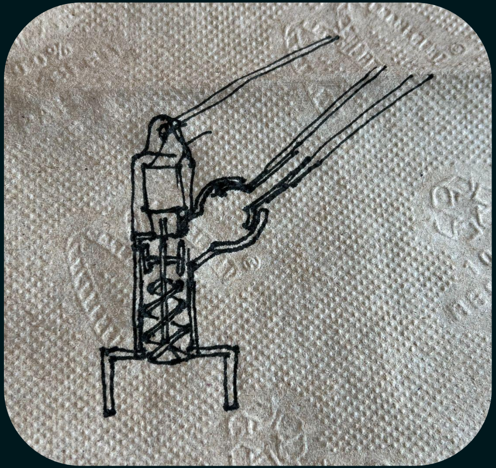
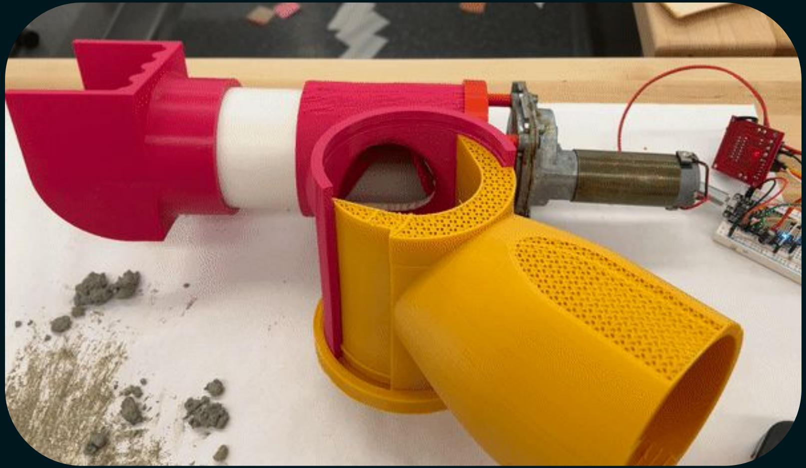
HARDWARE INTEGRATION

Flexibility and tolerance test successful for two-point connection

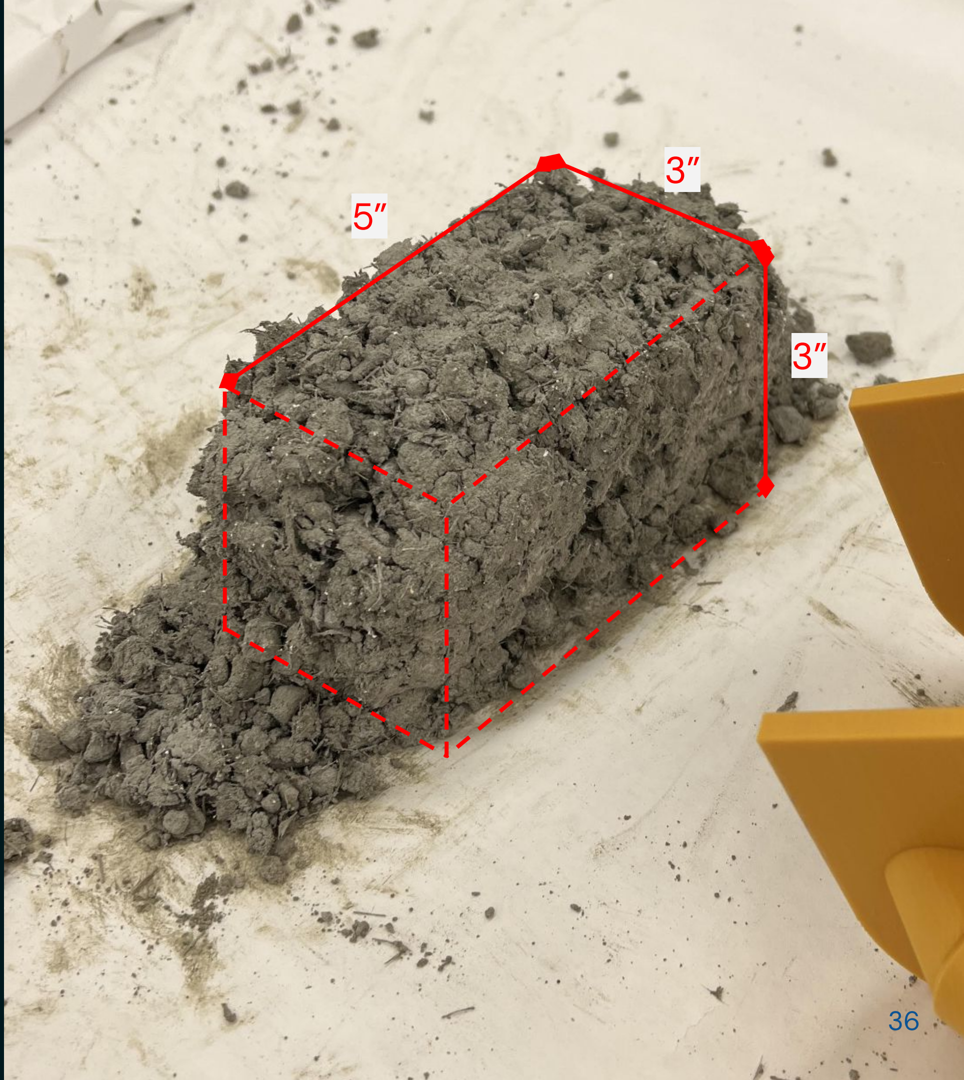




MATERIALS

Successfully Extruded small amount of material,

Not enough available for a second layer

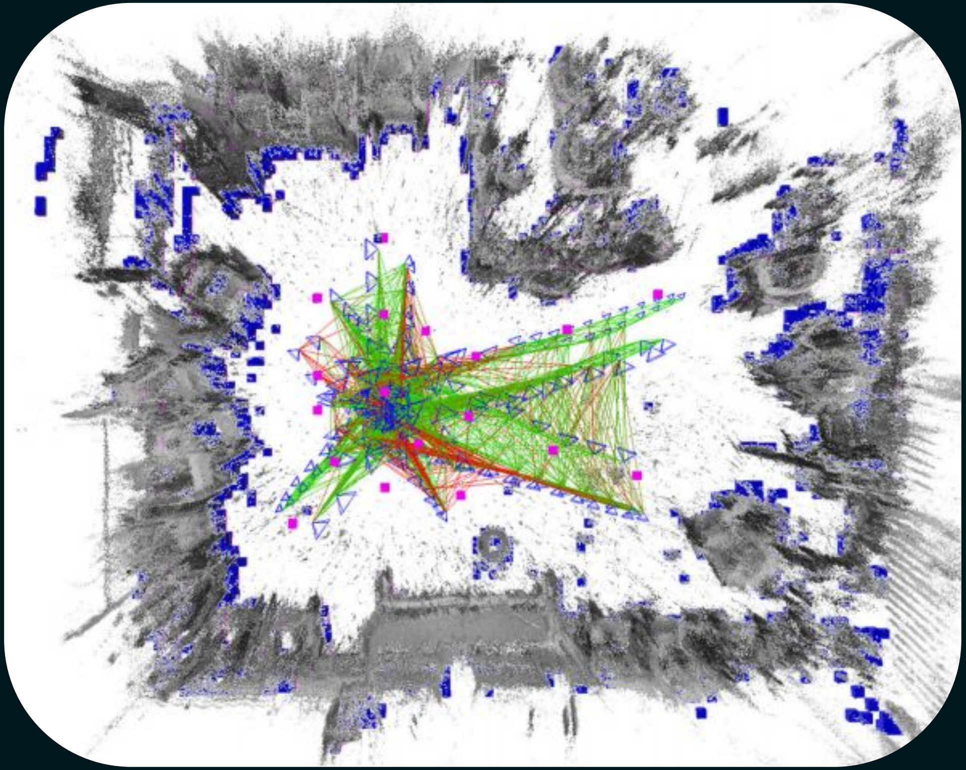


LOCATION TRACKING

LOCAL POSITIONING OPTIONS

What's the best way for a printer to know where it is in 3D space?

SLaM! Simultaneous Localization and Mapping... but which kind?

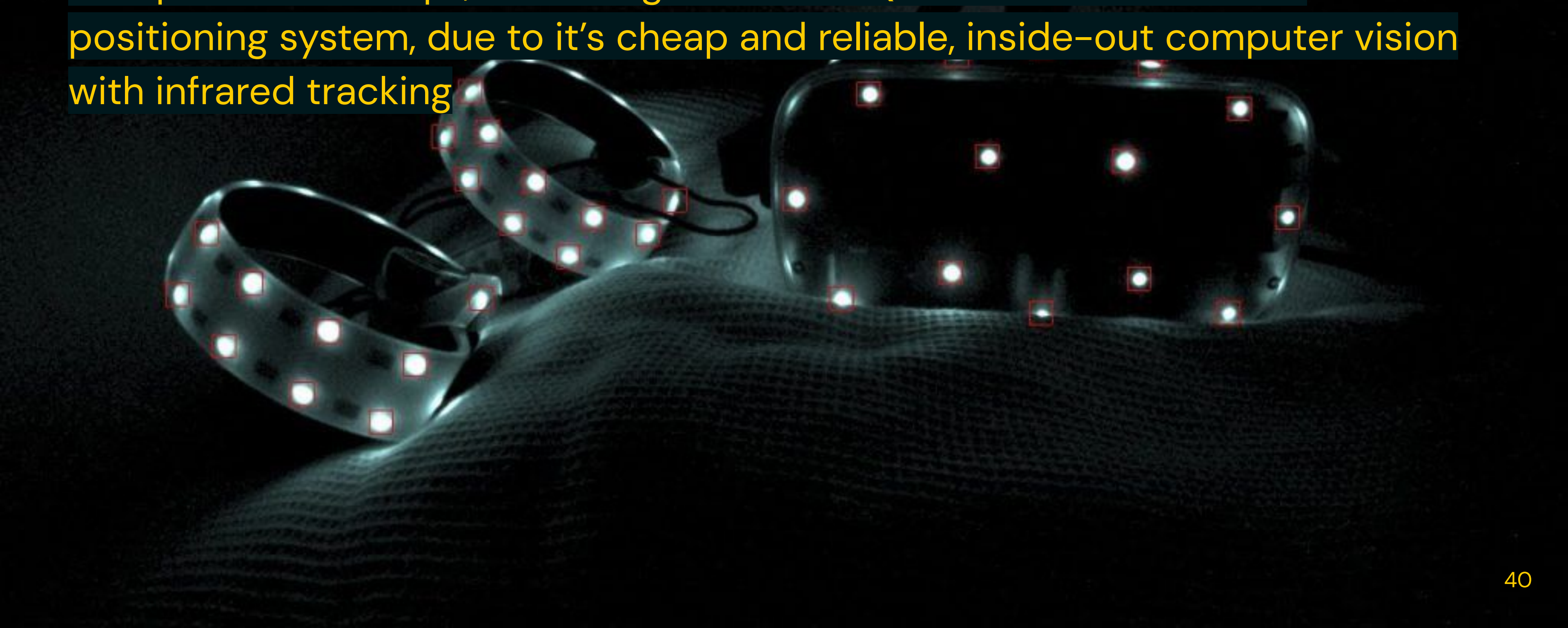


LOCAL POSITIONING OPTIONS

LPS METHOD	PROS	Cons
Time of Flight	Great for Z axis travel	Requires movement, accuracy dependant on distance to object
GPS	Global network, readily available	Accurate within 4.9m / 16ft
Ultra Wide Band Triangulation	Can “see” around corners,	Requires external triangulation points, accurate within 10cm / 4in
LiDAR	Accurate, active sensing source, no external points required, works in the dark,	New tech, very expensive
Computer Vision (Outside in)	Cheap, accurate to 1mm, easily accessible	Requires external triangulation
Computer Vision (Inside Out)	Cheap, accurate to 1mm, easily accessible, no external points required	Does not work in the dark
Computer Vision (Inside Out) + Infrared	**Cheap, accurate to 1mm, easily accessible, active sensing source, no external points required, works in the dark**	**Trouble working when it’s too bright out**

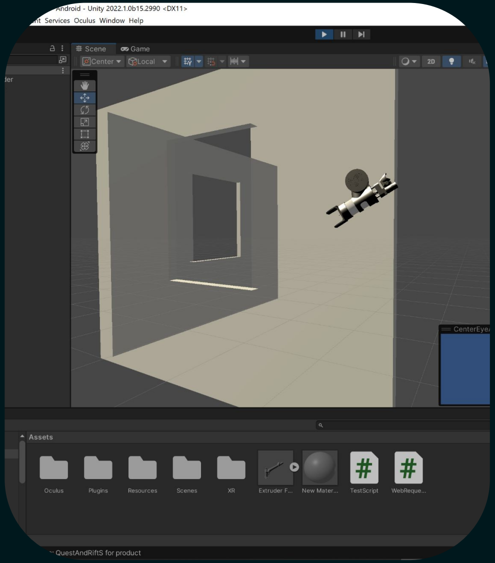
LOW-COST COMPUTER VISION

As a proof of concept, I am using an Oculus Quest 2 to create a local positioning system, due to it’s cheap and reliable, inside-out computer vision with infrared tracking

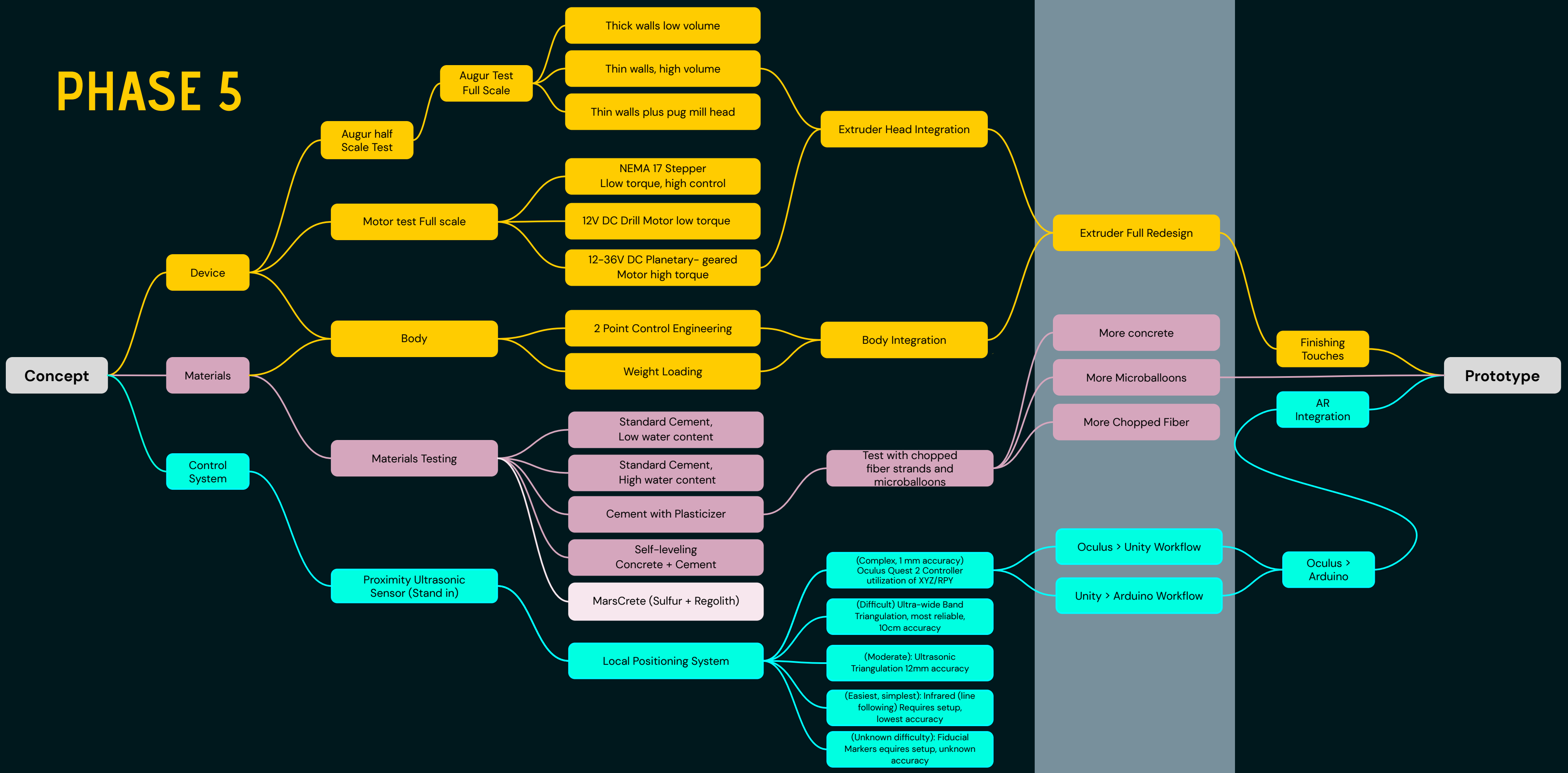


CONTROL SYSTEM

Developed a Unity Program and sideloaded to the Oculus in developer mode. Shows surroundings while **tracking geometry** attached to controller locations.



PHASE 5



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INTEGRATION

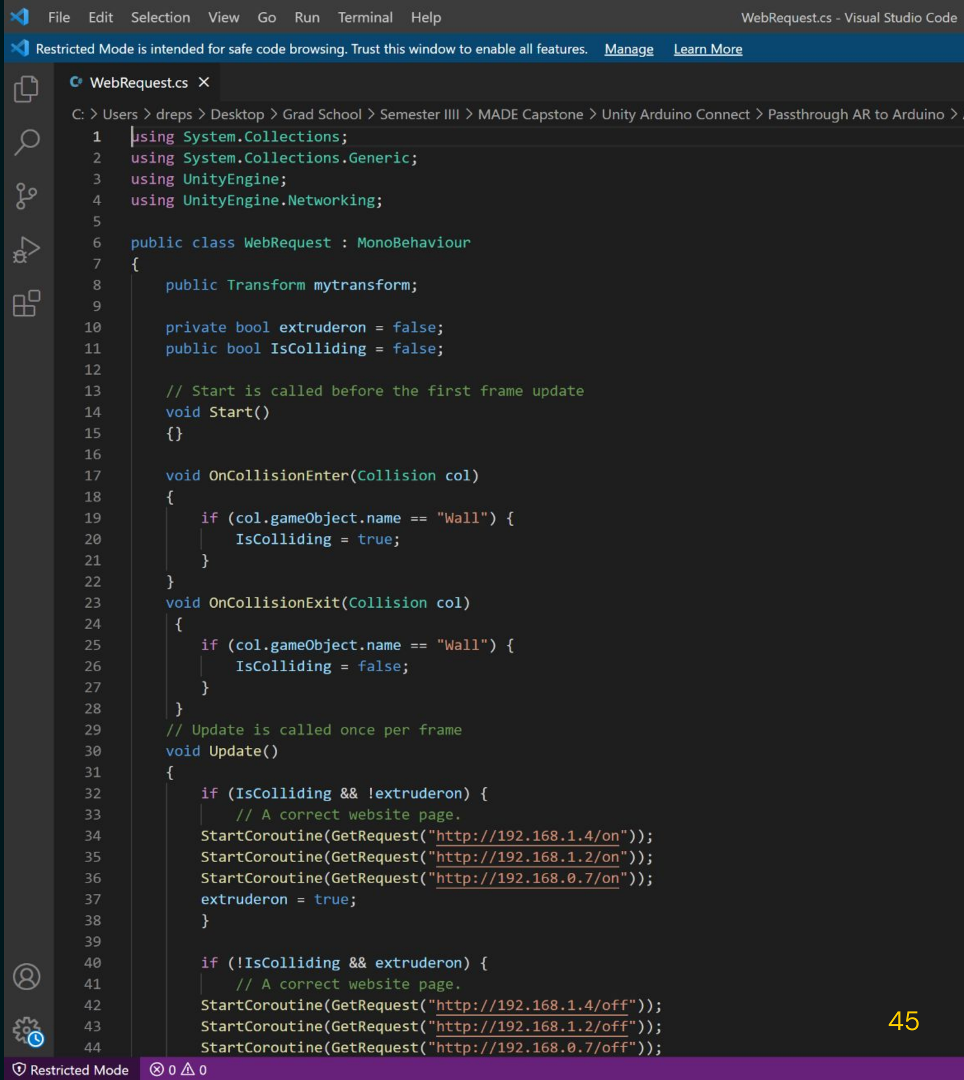
Full integration achieved

MOBILITY TEST

Testing users with different body types

CONTROL SYSTEM

Wrote a C# Script to detect collisions with “house geometry” and send “On/Off” signals to motor controller over WiFi



CONTROL SYSTEM

Wrote C++ code to receive "On/Off" signal over WiFi, and input proximity data from the Ultrasonic sensor to prevent motor from running when not on top of anything

File Edit Sketch Tools Help

Wifi_Extruder_Indicators §

```
R/*
  To upload through terminal you can use: curl -F "image=@firmware.bin" extruder.local/update
*/
#include <Adafruit_NeoPixel.h>
#include <ESP8266WiFi.h>
#include <WiFiClient.h>
#include <ESP8266WebServer.h>
#include <ESP8266mDNS.h>

//const char* ssid     = "NETGEAR51";         // The SSID (name) of the Wi-Fi network you want to
//const char* password = "newflute351";

#ifndef STASSID
#define STASSID "NETGEAR51"
#define STAPSK  "newflute351"
#endif

const char* host = "extruder";
const char* ssid = STASSID;
const char* password = STAPSK;

#define echoPin D6 // attach pin 2 Arduino to pin Echo of HC-SR04
#define trigPin D7 //attach pin 3 Arduino to pin Trig of HC-SR04
#define DCPositive D3
#define DCGround D4
#define DCData D2
#define Indicator D5
#define Vibrate D8
const int buzzer = D1;

// defines variables
long duration; // variable for the duration of sound wave travel
int distance; // variable for the distance measurement

Adafruit_NeoPixel pixels = Adafruit_NeoPixel(24, Indicator);

uint8_t  offset = 0; // Position of Indicator
uint32_t color  = 0x9FC5E8; // Start cyan

int ExtruderOn = 0;
```

CONTROL SYSTEM

Drill Battery (12V)

ESP8266

DC Motor Driver

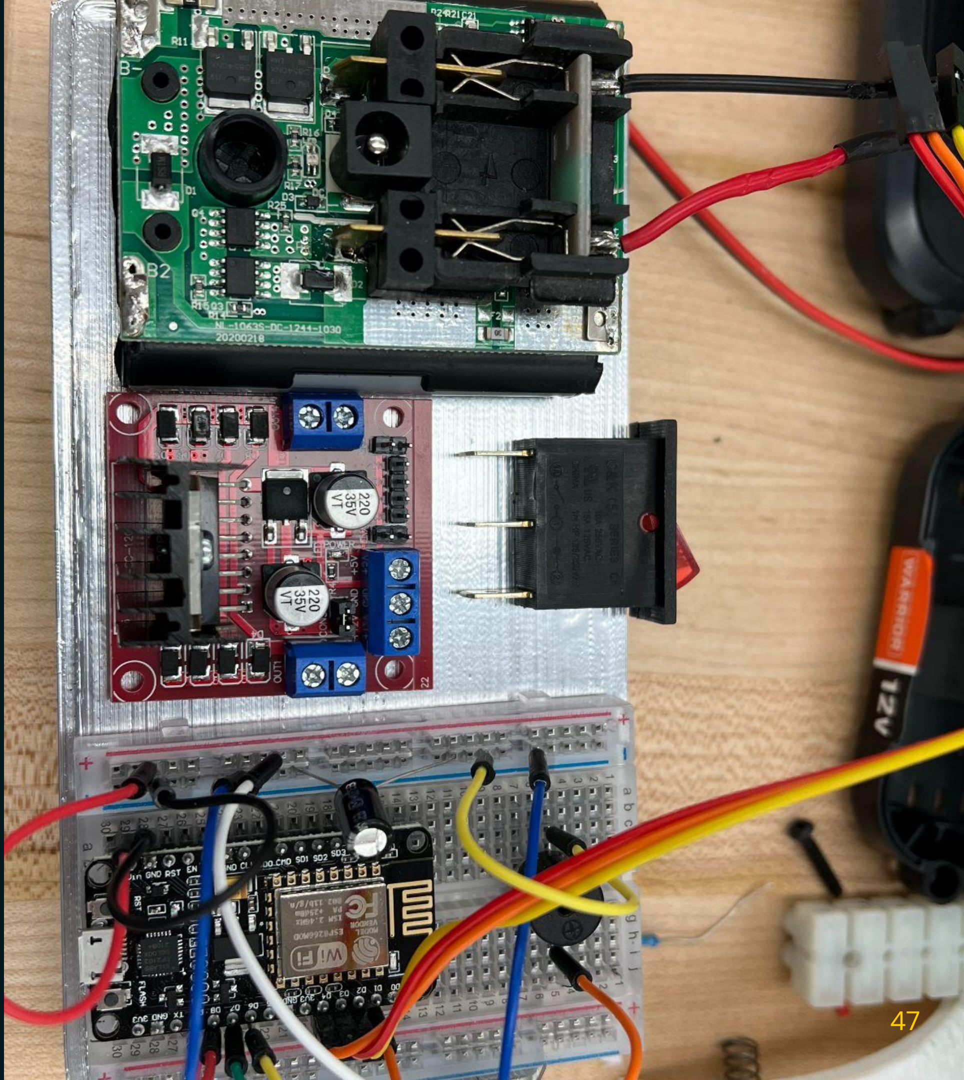
Windshield Wiper Motor (Brevel 780)

Switch

Buzzer

Adafruit NeoPixel Ring (24)

Ultrasonic Sensor HC-SR04



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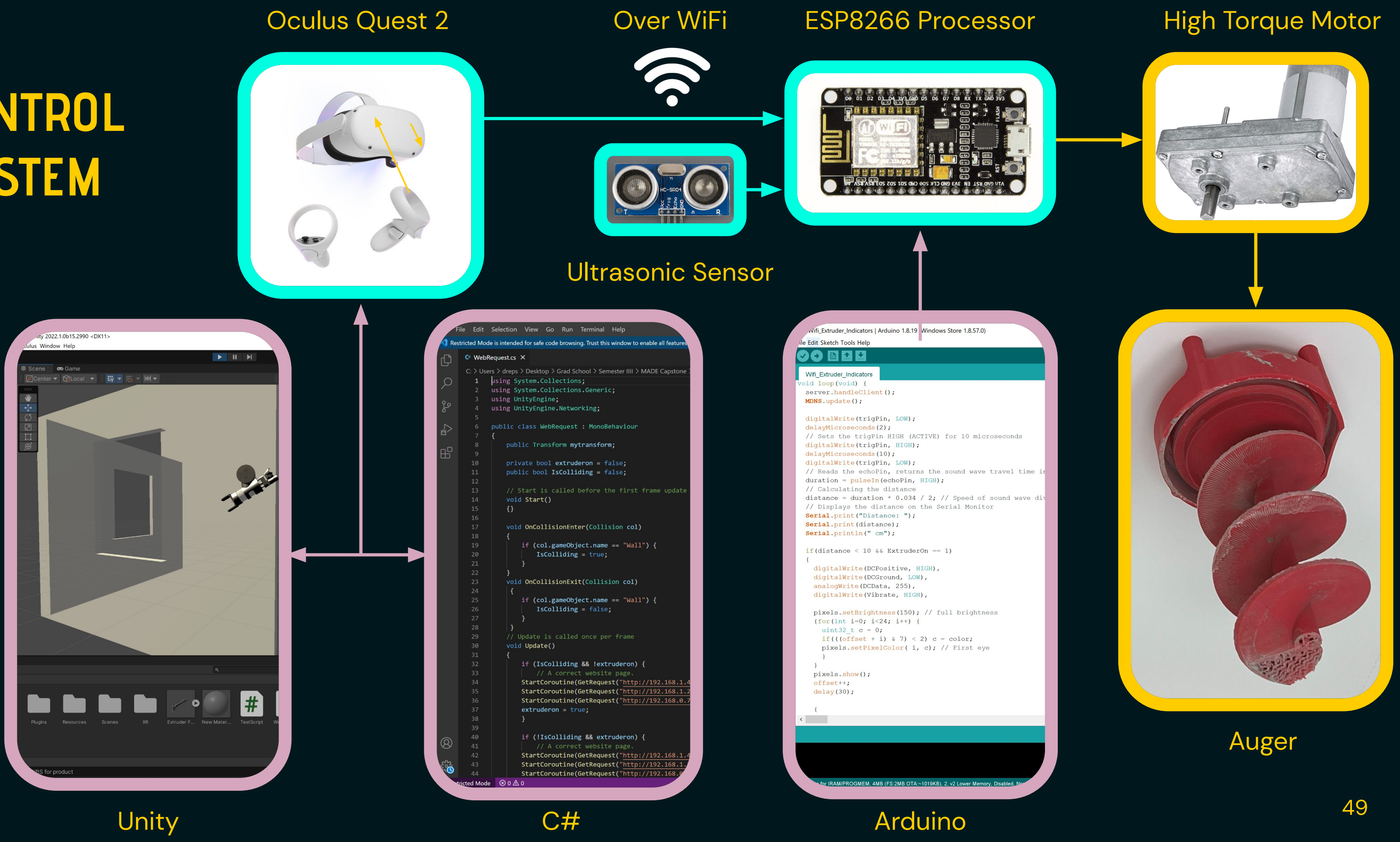
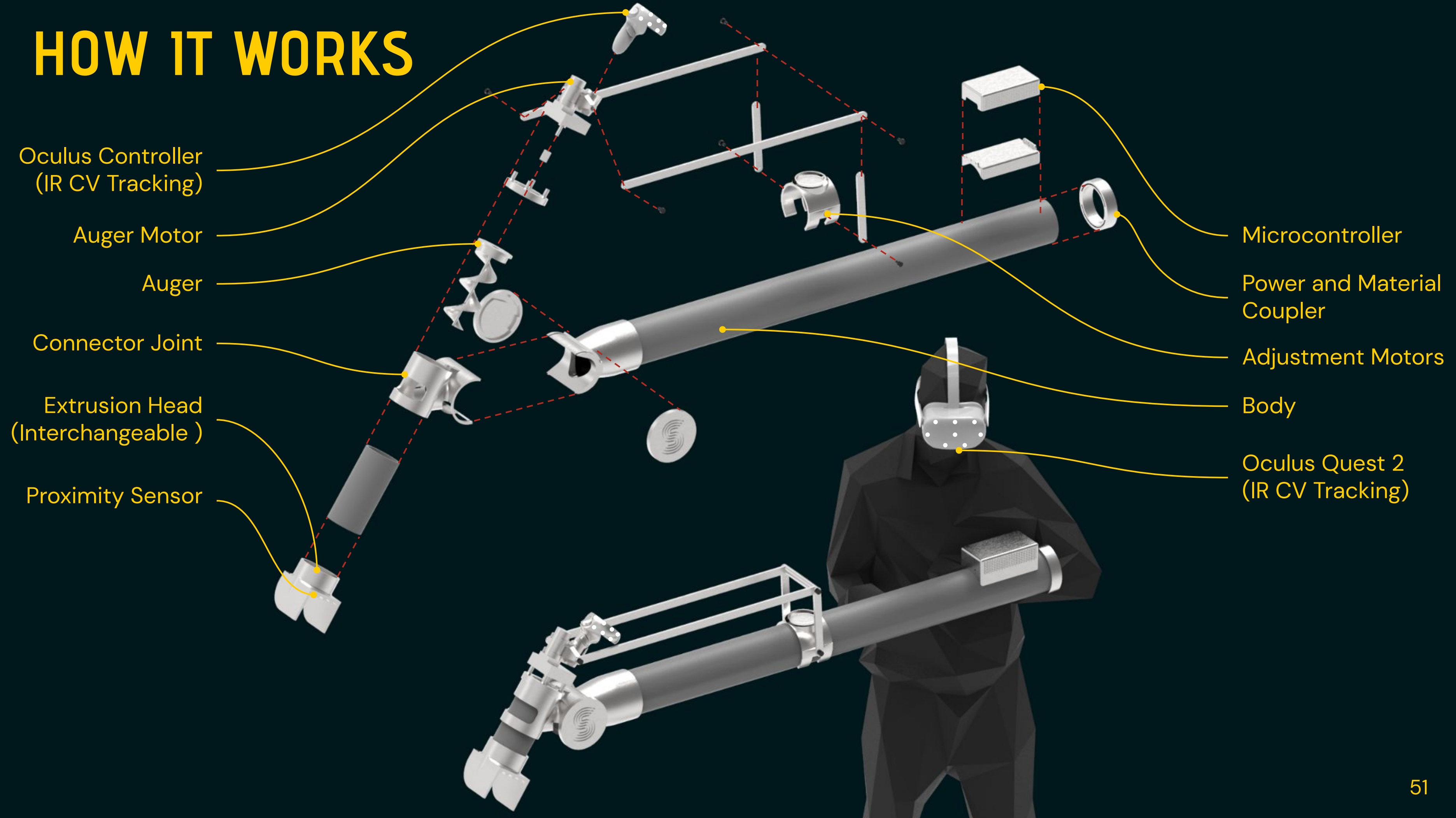
(Moderate): Ultrasonic Triangulation 12mm accuracy
(Easiest, simplest): Infrared (line following) Requires setup, lowest accuracy
(Unknown difficulty): Fiducial Markers equires setup, unknown accuracy
Oculus > Unity Workflow
Unity > Arduino Workflow
Oculus > Arduino
Finishing Touches
AR Integration
Prototype

CONTROL SYSTEM



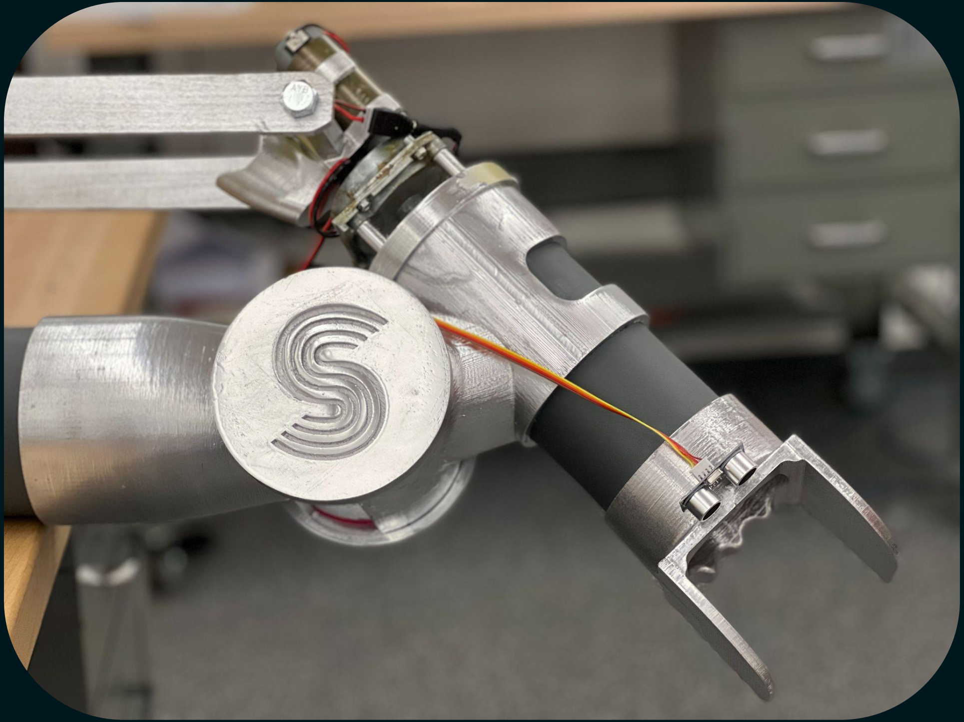
CONTROL SYSTEM

HOW IT WORKS



Oculus Controller
(IR CV Tracking)
Auger Motor
Auger
Connector Joint
Extrusion Head
(Interchangeable)
Proximity Sensor
Microcontroller
Power and Material
Coupler
Adjustment Motors
Body
Oculus Quest 2
(IR CV Tracking)

INTEGRATION




LIVE
DEMO

WHAT I LEARNED

Computer Visions is AMAZING.

Location-based extrusion will work.

Mass adoption, however...

WHAT I LEARNED

The stabilization required to replicate accuracy would likely make this tool too heavy for a human to use

The way forward is to switch to robotics, and use inverse kinematics (Boston Dynamic's Spot or ATLAS robots)

Future Developments

I will be continuing work on this project with a generous grant from the **Rhode Island Space Grant Consortium** and **NASA**.

Prototyping & Testing

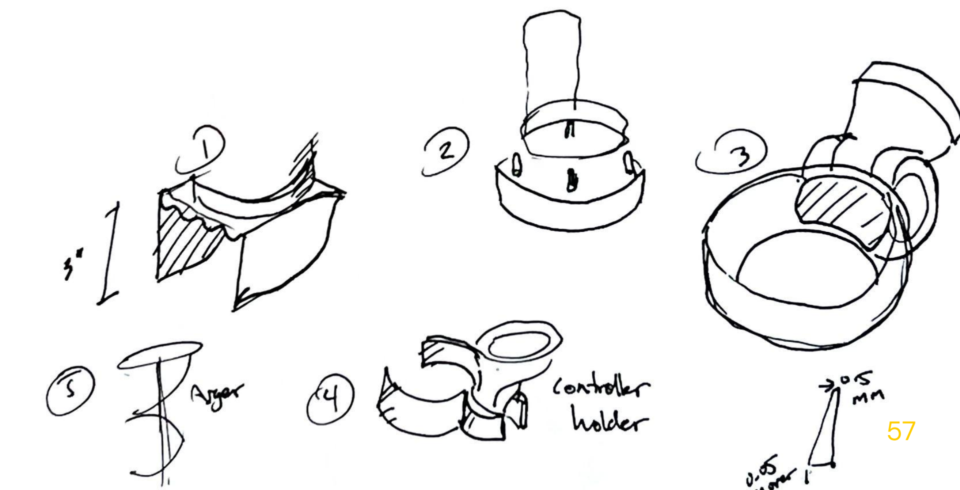
Hardware

Materials

Location Sensing

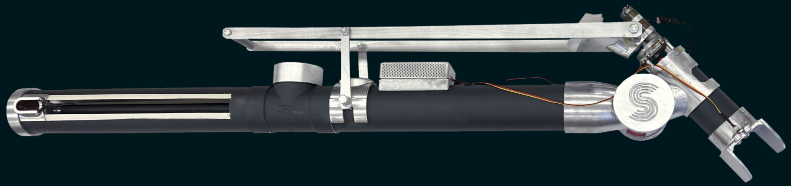
AR Visual Interface

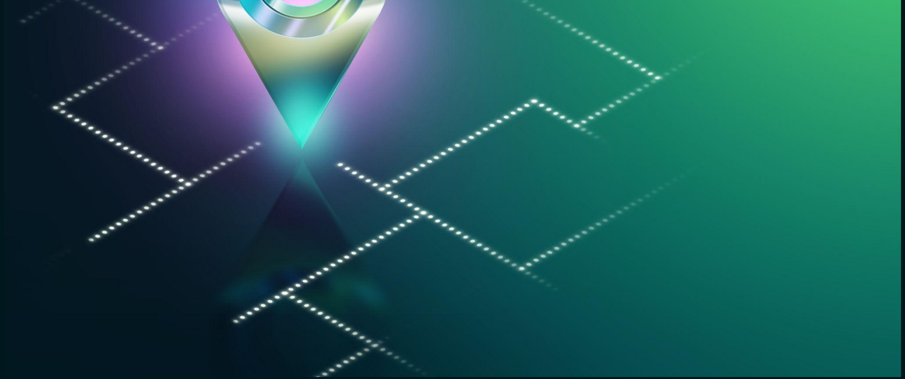
User Testing



Final Product

While I was able to create a positionally aware control system from off-the-shelf hardware, I was not able to extrude material as originally proposed.





Construction is Inefficient

Construction is an incredibly inefficient industry.

XX much concrete, XX much water, XX much energy!

On top of that, labor and materials shortages are driving up costs like crazy!

define innificency

How are these ultimately reduced

Concrete water cost energy time

What can be achieved on each

Construction is Inefficient

The average home takes 7 months to build

1. Clear Property	2. Level Site	3. Dig trenches	4. Prepare Foundations
5. Install Footings	6. Pour Foundation	7. Install Formwork	8. Pour columns & shear walls
9. Plumbing connections	10. Build Frame	11. Apply Exterior Sheathing	12. Install Windows and Doors
13. Install HVAC	14. Rough-in Plumbing	15. Install Electrical	16. Build out Roof
17. Add Insulation	18. Drywall is hung, painted	19. Exterior Finishes installed	20. Flooring laid
21. Window trim installed	22. Casework installed	23. Fixtures installed	**23 Steps Total**

3D Printing to the Rescue?

Construction printing has the potential to **democratize construction** beyond just construction companies by:

Ditching formwork to build faster

Using less material

> Being less wasteful.

> Being cheaper

1. Clear Property	2. Level Site	3. Dig trenches	4. Prepare Foundations
5. Install Footings	6. Pour Foundation	~~Install Formwork~~	~~Pour columns & shear walls~~
7. Plumbing connections	~~Build Frame~~	~~Apply Exterior Sheathing~~	8. Install Windows and Doors
9. Install HVAC	10. Rough-in Plumbing	11. Install Electrical	12. Build out Roof
~~Add Insulation~~	13. Drywall is hung, painted	~~Exterior Finishes installed~~	14. Flooring laid
15. Window trim installed	16. Casework installed	17. Fixtures installed	**17 Steps Total**

3D Printing to the Rescue?

Companies around the world are starting to take advantage is such tools and simplify this process:

ICON3D, Texas

COBOD, Denmark, Africa

WASP, Italy

In reality...

This is a technology in its infancy.

These robots are... dumb:

They **don't know where they are**, and work in an **open loop system**

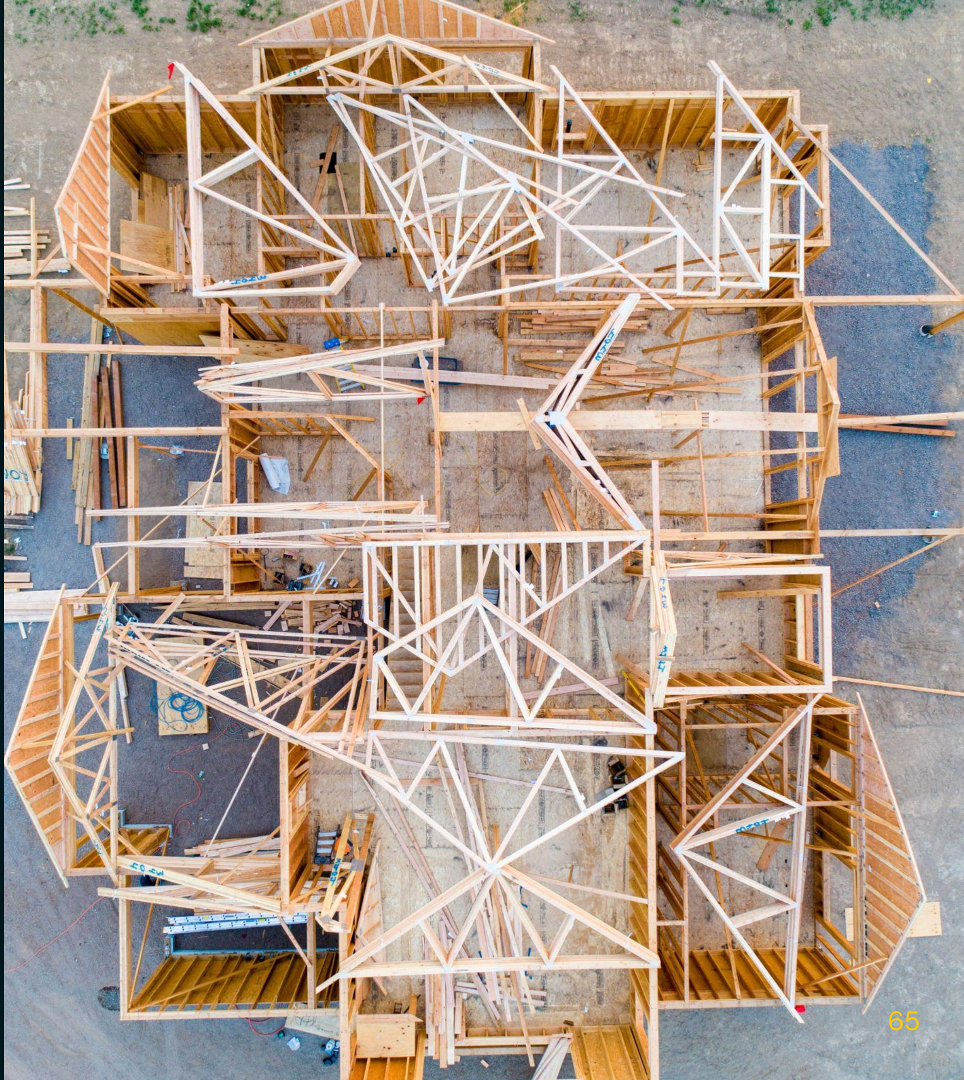
>They require **massive gantry systems** larger than the building they're printing, and leave a "trail of breadcrumbs" to follow home

>They are therefore **hard to transport**, set up, and are very logistically challenging to even start

>not much cheaper or faster than traditional processes

Statement of Intent

How can we create a smarter construction printer that is positionally aware and uses less infrastructure to fully unlock this technology's potential?

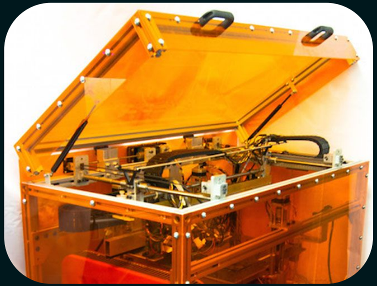


Precedent Projects

"Smart" printers are being considered to address this issue

But regardless of how each device moves, its control system is the real secret sauce.

None of these solutions address a system that is fully aware of its location



MIT 3D Printer that scans every layer and adjusts for errors

3D Printer Drone, Gensler

Mobile Build Platform by Stephen Keating for MIT Media Lab

AMBOTS – Dr. Wenchao Zhou, U Arkansas

A Better Builder

By creating a high-precision, closed loop local positioning system, a construction printer can:

- Self-check errors
- Forego site excavation
- Ditch the gantry
- Be **Infinitely Scalable**

Simply drop and go.

1. Clear Property	~~Level Site~~	~~Dig trenches~~	~~Prepare Foundations~~
~~Install Footings~~	~~Pour Foundation~~	~~Install Formwork~~	~~Pour columns & shear walls~~
2. Plumbing connections	~~Build Frame~~	~~Apply Exterior Sheathing~~	3. Install Windows and Doors
4. Install HVAC	5. Rough-in Plumbing	6. Install Electrical	7. Build out Roof
~~Add Insulation~~	8. Drywall is hung, painted	~~Exterior Finishes installed~~	9. Flooring laid
10. Window trim installed	11. Casework installed	12. Fixtures installed	**12 Steps Total**

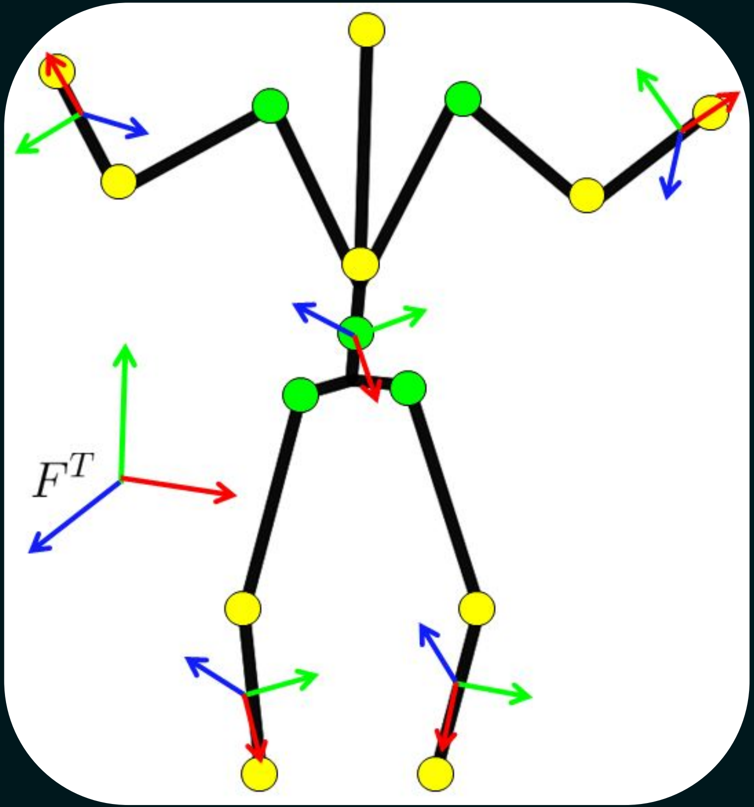
Prototype and Goal

The LPS can only track the position of the printer head.

An **inverse kinematics** system must move it to where it needs to be.

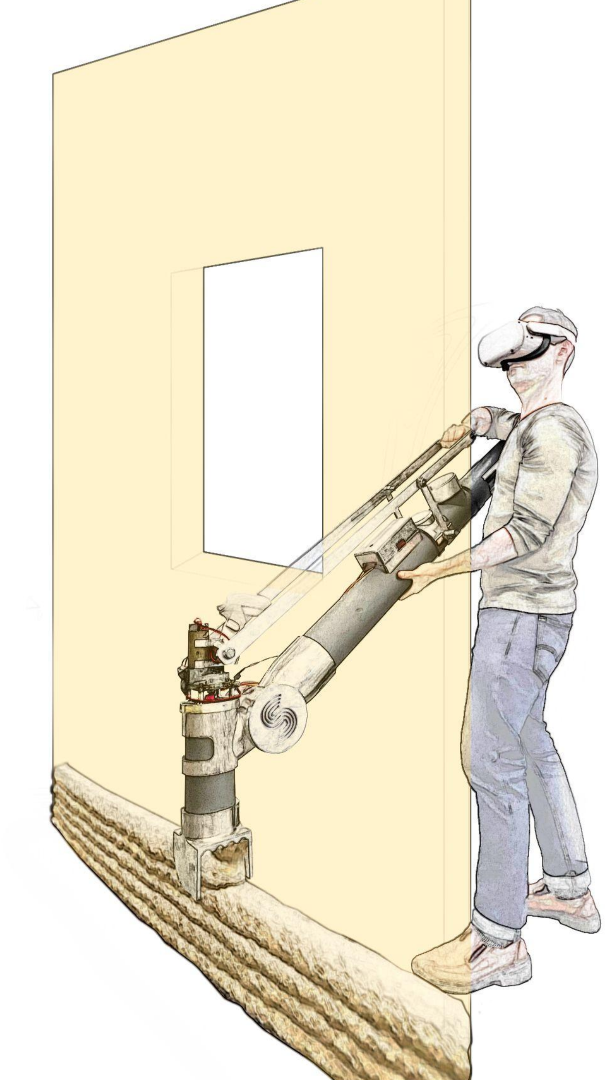
The simplest way to do this with an Oculus is to outsource the job to a Human.

This effectively turns a human into a 3d printer. **My goal was to use this tool to build a wall in just a few minutes**, to prove that someone with no experience could use it. The interface is simple, and is augmented by AR.



Challenges

1. Develop a device that one person can hold
2. Develop extrudable materials
3. Develop a device that can extrude that material
4. Extract Computer Vision data from collector (Oculus), live
5. Develop control system from live data
6. Develop Augmented Reality interface; “visual Gcode” for humans



Demo

What I Learned

Unity

Oculus XR

C#

Arduino IDE

IoT

Rheology

GD&T

What I Learned

Works **RIGHT NOW** – in 15 years robots could do this

But for right now, it's good to have humans involved.

Only humans can currently predict all possible ways a printer could fail, and account for them.

If construction printing fails 1 time out of 100, that's one too many.

What I Learned

How much material would you save?

PROJECT SYNOPSIS
What did you learn from doing this project?

Provide Evidence

Interviews w/ NASA people

Construction workers?

DEMO

Moving Forward

Ultimately, we could mobilize this on a robot that utilized inverse kinematics, with time, research and investment

This prototype successfully proves that inside out computer vision can effectively map space in 3D with cheap cameras, remember that space, and then utilize simple infrared tracking on what is basically an android phone, to process it live. A machine that utilized inverse kinematics could do a more efficient job and print things live.

ROHAN NOTES

Audience will be tired
5-6 critical slides for story
*37 what i learned
Technical content in appendix section?
Print out copies of slide deck - hand them to people
Show, don't tell
Show actual thing at beginning - say it's name! Should be focus

What you did, why'd you do it, what problem is it solving, why do I care? What did you learn, what were your failures? Therefore, therefore, therefore
SHOW THE VISION
5-6 slides? Will prevent people from asking dumb questions -keep it sparse
Deck you handout, include content
What is the main takeaway with all these slides??

Hard research should go into book, takeaways should go into deck, 3 bullets a slide

Pop - through imagery. Show the product as much as possible - audience leaving with image stuck in their heads

Nicole notes

Not so much text

More visuals

Turn lists of steps into chart?

Should have more of a testing focus

Requirements

Immediately sensing terrain will orient the device quickly

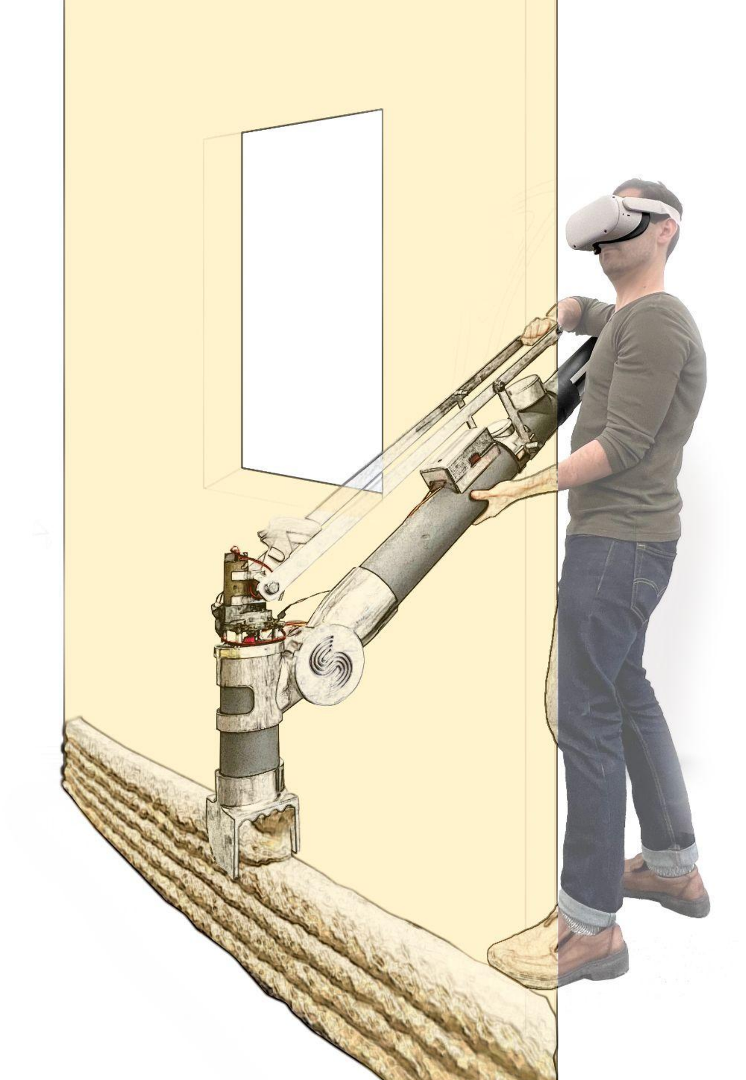
Understanding site position foregoes need for massive gantries

A handheld tool can go anywhere a person can

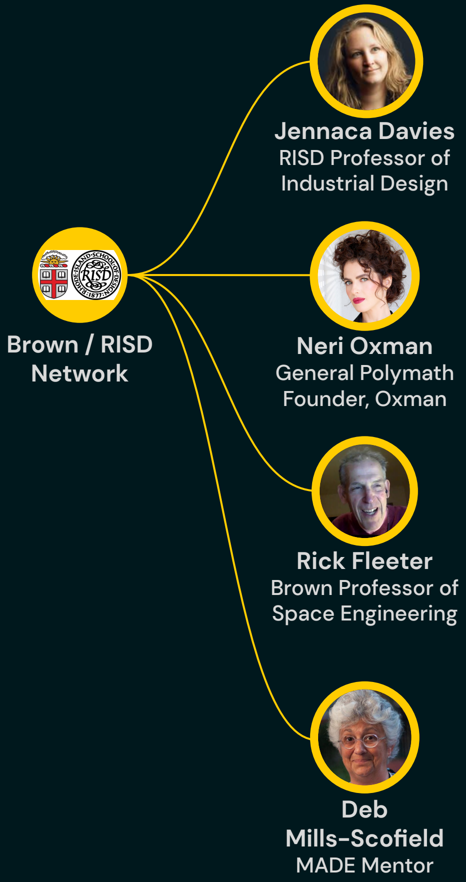
A visual interface transcends language

Positional data control merely requires mobility from operator

A self-aware tool with onboard sensors and human mobility has no constrained print area



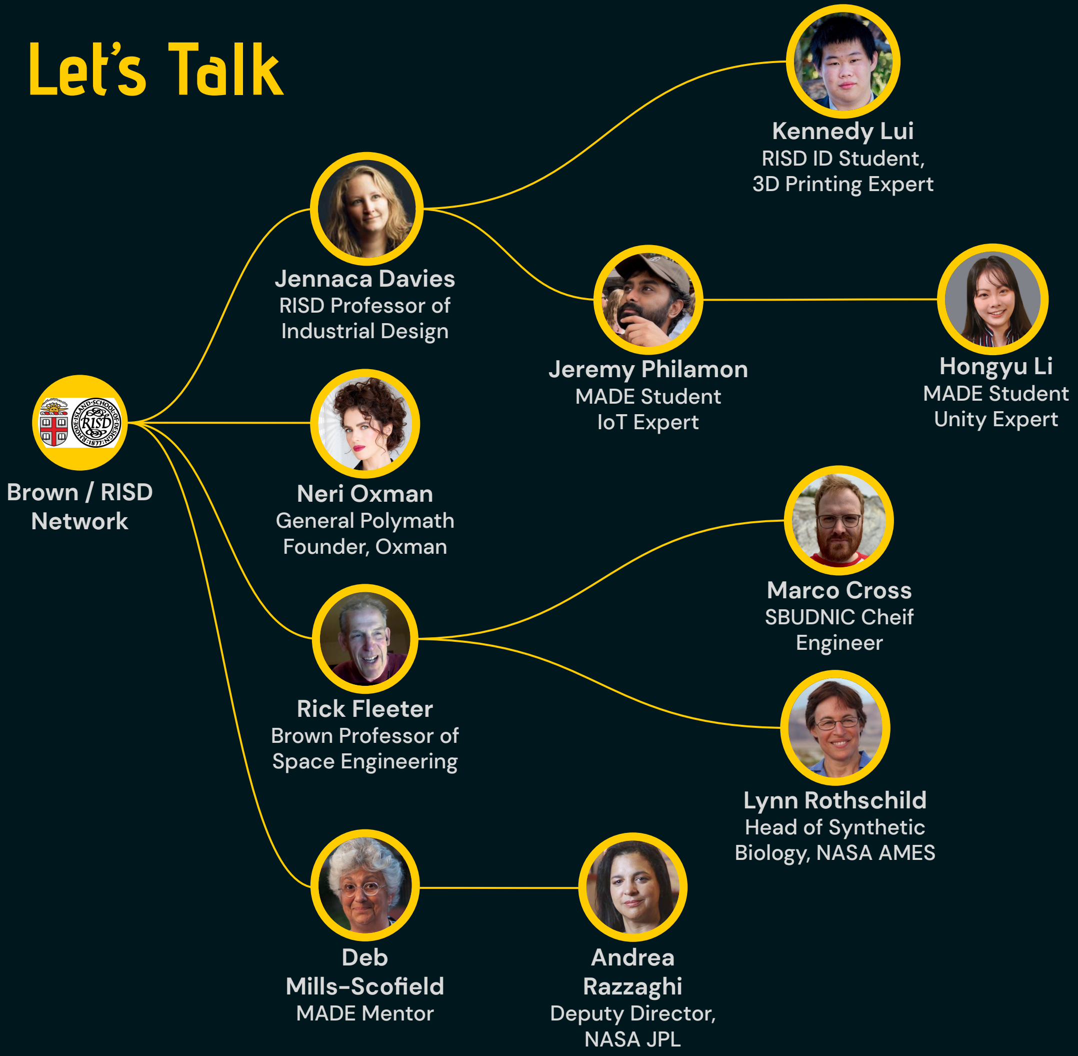
Let's Talk



WHY DID YOU TALK TO ALL THESE PEOPLE? WHAT DO THEY OFFER

Not a random walk: Why did you talk to them, what do the provide?

Let's Talk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RISD ID Student,
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MADE Student
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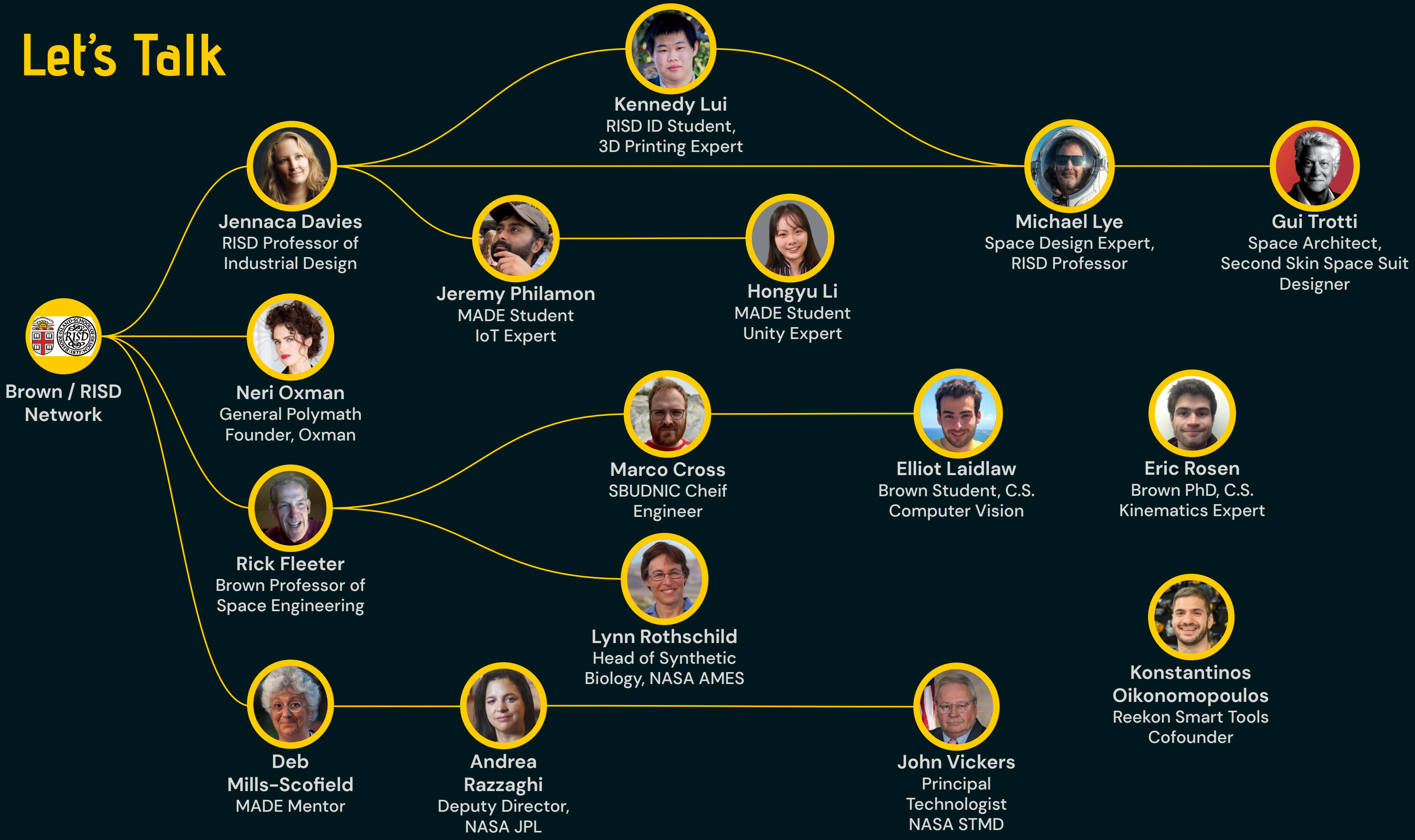
Brown / RISD
Network
Neri Oxman
General Polymath
Founder, Oxman
Marco Cross
SBUDNIC Cheif
Engineer
Rick Fleeter
Brown Professor of
Space Engineering
Lynn Rothschild
Head of Synthetic
Biology, NASA AMES
Deb
Mills-Scofield
MADE Mentor
Andrea
Razzaghi
Deputy Director,
NASA JPL

Let's Talk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Michael Lye
Space Design Expert,
RISD Professor
Gui Trotti
Space Architect,
Second Skin Space Suit
Designer
Jeremy Philamon
MADE Student
IoT Expert
Hongyu Li
MADE Student
Unity Expert
Brown / RISD
Network
Neri Oxman
General Polymath
Founder, Oxman
Marco Cross
SBUDNIC Cheif
Engineer
Elliot Laidlaw
Brown Student, C.S.
Computer Vision
Eric Rosen
Brown PhD, C.S.
Kinematics Expert
Rick Fleeter
Brown Professor of
Space Engineering
Lynn Rothschild
Head of Synthetic
Biology, NASA AMES
Konstantinos
Oikonomopoulos
Reekon Smart Tools
Cofounder
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John Vickers
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Technologist
NASA STMD