
JPL

1
00:00:02,768 --> 00:00:06,239
- [Voiceover] NASA's Jet
Propulsion Laboratory presents

2
00:00:06,272 --> 00:00:08,975
the von Karman Lecture,
a series of talks

3
00:00:09,008 --> 00:00:12,612
by scientists and engineers
who are exploring our planet,

4
00:00:12,645 --> 00:00:16,216
our solar system, and
all that lies beyond.

5
00:00:17,083 --> 00:00:20,820
(uplifting, enchanted music)

6
00:00:28,394 --> 00:00:29,462
- Good evening,
ladies and gentleman.

7
00:00:29,495 --> 00:00:31,397
How's everyone tonight?

8
00:00:31,430 --> 00:00:32,665
- [Audience] Good.

9
00:00:32,698 --> 00:00:34,200
- Good, thank you very
much for coming out

10
00:00:34,233 --> 00:00:36,936
between the Thursday night
football, the baseball game,

11
00:00:36,969 --> 00:00:39,672
and the candidate dinner

thing, we're really grateful

12
00:00:39,705 --> 00:00:42,141
you made it out
tonight. (laughs)

13
00:00:42,174 --> 00:00:44,610
So the ability to rove
the surface of Mars

14
00:00:44,643 --> 00:00:47,413
has revolutionized JPL missions.

15
00:00:47,446 --> 00:00:50,883
With more advanced mobility,
new targets like cliff faces,

16
00:00:50,916 --> 00:00:54,220
cave ceilings, and the surfaces
of asteroids and comets

17
00:00:54,253 --> 00:00:56,155
could potentially be explored.

18
00:00:56,188 --> 00:00:57,523
Tonight's talk will
present the work

19
00:00:57,556 --> 00:01:00,493
of JPL's Robotic
Rapid Prototyping Lab,

20
00:01:00,526 --> 00:01:02,662
which is currently
working on grippers

21
00:01:02,695 --> 00:01:05,031
for NASA's Asteroid
Redirect Mission.

22
00:01:05,064 --> 00:01:07,967
This mission plans to
extract a 20 ton boulder

23
00:01:08,000 --> 00:01:09,602
from the surface of an asteroid,

24
00:01:09,635 --> 00:01:11,838
then actually alter it's orbit,

25
00:01:11,871 --> 00:01:13,606
using a method
that could be used

26
00:01:13,639 --> 00:01:16,776
to prevent future asteroid
impacts with Earth.

27
00:01:16,809 --> 00:01:19,445
Our guest will also talk
about other inspired adhesives

28
00:01:19,478 --> 00:01:23,950
and designs currently being
tested on Earth and in space.

29
00:01:23,983 --> 00:01:25,718
Tonight's guest is
the group leader

30
00:01:25,751 --> 00:01:28,688
of the Extreme Environment
Robotics Group at JPL

31
00:01:28,721 --> 00:01:32,291
and the head of the Robotic
Rapid Prototyping Laboratory.

32
00:01:32,324 --> 00:01:34,427

He received two bachelor's
degrees from MIT

33
00:01:34,460 --> 00:01:36,796
in Mechanical Engineering
and Creative Writing,

34
00:01:36,829 --> 00:01:39,398
and an MS and Ph.D.
from Stanford University

35
00:01:39,431 --> 00:01:40,967
in Mechanical Engineering.

36
00:01:41,000 --> 00:01:42,535
At JPL, he currently works on

37
00:01:42,568 --> 00:01:44,804
the Asteroid Redirect
Mission, leading a team

38
00:01:44,837 --> 00:01:48,341
that is developing the robotic
grippers for the spacecraft.

39
00:01:48,374 --> 00:01:50,343
Additionally, he
formulates and leads

40
00:01:50,376 --> 00:01:52,545
several technology
development projects

41
00:01:52,578 --> 00:01:55,014
and also assists
work in JPL's office

42
00:01:55,047 --> 00:01:57,850
of the Chief Scientist
and Chief Technologist.

43
00:01:57,883 --> 00:01:59,285
He and his work have
been featured in

44
00:01:59,318 --> 00:02:02,555
The Economist, Time Magazine,
and as a Popular Science

45
00:02:02,588 --> 00:02:05,091
top 100 innovation of the year,

46
00:02:05,124 --> 00:02:07,493
as well as on the
Discovery Channel, BBC,

47
00:02:07,526 --> 00:02:11,130
and in JPL's own Crazy
Engineering on YouTube.

48
00:02:11,163 --> 00:02:14,600
In 2015, he was awarded one
of JPL's highest honors,

49
00:02:14,633 --> 00:02:16,602
the Lew Allen Award,
which recognizes

50
00:02:16,635 --> 00:02:21,340
individual accomplishments,
pardon me, or leadership

51
00:02:21,373 --> 00:02:24,410
in scientific research or
technological innovation

52
00:02:24,443 --> 00:02:27,046
by JPL employees
during the early years

53
00:02:27,079 --> 00:02:28,881
of their professional careers.

54
00:02:28,914 --> 00:02:31,117
Ladies and gentlemen, please
help me welcome tonight's guest

55
00:02:31,150 --> 00:02:32,418
Dr. Aaron Parness.

56
00:02:32,451 --> 00:02:36,055
(audience applause)

57
00:02:36,088 --> 00:02:37,090
- Thank you.

58
00:02:39,858 --> 00:02:43,196
Hello, everyone, thank
you for coming out.

59
00:02:43,229 --> 00:02:44,931
It's my honor, actually,
to talk to you tonight

60
00:02:44,964 --> 00:02:47,200
about our robotic grippers.

61
00:02:49,001 --> 00:02:50,336
Let's see here.

62
00:02:50,369 --> 00:02:53,439
So we have three basic
technologies you'll learn about.

63
00:02:53,472 --> 00:02:55,875
On the left is a
gecko-inspired adhesive.

64

00:02:55,908 --> 00:02:59,111
Geckos use lots of tiny hairs
on the surfaces of their feet

65
00:02:59,144 --> 00:03:02,281
to stick using van
der Waals forces.

66
00:03:02,314 --> 00:03:04,750
In the center is a physics
that we all learned

67
00:03:04,783 --> 00:03:06,619
when we were about
five or six years old,

68
00:03:06,652 --> 00:03:09,121
walking with wool
socks across the carpet

69
00:03:09,154 --> 00:03:12,024
to shock our siblings or
rubbing the balloon on our head

70
00:03:12,057 --> 00:03:13,893
to get it to stick to the wall.

71
00:03:13,926 --> 00:03:14,860
So we were able to harness that

72
00:03:14,893 --> 00:03:17,396
for sticking to things in space.

73
00:03:17,429 --> 00:03:20,766
And on the right you
see an insect-inspired

74
00:03:20,799 --> 00:03:23,903
adhesive method
using claws or hooks.

75
00:03:23,936 --> 00:03:28,107
This is good for penetrable
surfaces like soft rocks or wood

76
00:03:29,275 --> 00:03:32,411
and for rough surfaces
that are very sturdy

77
00:03:32,444 --> 00:03:34,113
like volcanic rocks.

78
00:03:35,481 --> 00:03:38,217
So the talk is broken
up into four chapters.

79
00:03:38,250 --> 00:03:41,153
We'll start with ARM, the
Asteroid Redirect Mission.

80
00:03:41,186 --> 00:03:43,656
And then we'll move,
actually, backwards in time

81
00:03:43,689 --> 00:03:45,558
to talk about our
rock climbing robots.

82
00:03:45,591 --> 00:03:49,629
These have been in development
for about 10 or 12 years now.

83
00:03:49,662 --> 00:03:52,932
The third chapter is on
the gecko-like adhesives.

84
00:03:52,965 --> 00:03:57,169
And we'll wrap up with a
montage of videos and photos

85
00:03:57,202 --> 00:04:00,339
of some of our
prototypes in the lab.

86
00:04:00,372 --> 00:04:04,143
And I'll try and touch on the
iterative design principles

87
00:04:04,176 --> 00:04:07,780
we use and the rapid prototyping
techniques that enable us

88
00:04:07,813 --> 00:04:11,985
to make these robots very
fast and very cost effective.

89
00:04:13,485 --> 00:04:15,788
Okay, so ARM, the
Asteroid Redirect Mission.

90
00:04:15,821 --> 00:04:18,824
It's a NASA mission, JPL
is leading this mission.

91
00:04:18,857 --> 00:04:20,826
But there's a lot of partners.

92
00:04:20,859 --> 00:04:23,796
Goddard Space Flight Center is
developing the capture module

93
00:04:23,829 --> 00:04:26,666
with significant
contributions from Langley

94
00:04:26,699 --> 00:04:29,468
as well as some teams
back here at JPL.

95

00:04:29,501 --> 00:04:32,038
Glenn Research Center is
developing a high-power

96
00:04:32,071 --> 00:04:35,408
solar electric propulsion
system for this mission,

97
00:04:35,441 --> 00:04:38,644
and Johnson Space Center is
working on a follow-on mission

98
00:04:38,677 --> 00:04:40,646
that would send
astronauts to the boulder

99
00:04:40,679 --> 00:04:42,882
that we're collecting
off the surface.

100
00:04:42,915 --> 00:04:45,418
The spacecraft itself
is going to built by an

101
00:04:45,451 --> 00:04:48,354
industrial partner, and that's
in competition right now.

102
00:04:48,387 --> 00:04:50,056
So there are four
finalists competing

103
00:04:50,089 --> 00:04:52,592
to see who will build the bus.

104
00:04:54,026 --> 00:04:57,396
An animation here shows the
mission during the surface

105
00:04:57,429 --> 00:05:00,266

phase, which is a really
critical phase of the mission.

106
00:05:00,299 --> 00:05:01,901
We're scanning the asteroid.

107
00:05:01,934 --> 00:05:03,803
It's a giant spacecraft.

108
00:05:03,836 --> 00:05:07,440
From tip to tip, those solar
arrays are about 40 meters,

109
00:05:07,473 --> 00:05:12,044
or over 120 feet, much larger
than an NBA basketball court.

110
00:05:12,077 --> 00:05:14,513
We need all that power for
that high-power solar electric

111
00:05:14,546 --> 00:05:16,982
propulsion system, which
is really good for pushing

112
00:05:17,015 --> 00:05:21,754
heavy things like 20 ton
boulders around in space.

113
00:05:21,787 --> 00:05:25,558
As we land, we're gonna absorb
that landing with the legs,

114
00:05:25,591 --> 00:05:27,660
try and cushion ourselves
and use our thrusters

115
00:05:27,693 --> 00:05:30,529
to make sure we don't
bounce, as was what happened

116
00:05:30,562 --> 00:05:34,166
to the Philae lander on
the comet about a year ago.

117
00:05:34,199 --> 00:05:36,369
Asteroids are actually
notoriously hard to land on.

118
00:05:36,402 --> 00:05:39,638
The Japanese also failed in
an attempt about 12 years ago

119
00:05:39,671 --> 00:05:42,274
with a mission called Hayabusa.

120
00:05:42,307 --> 00:05:44,744
We'll use dexterous robotic
arms to place grippers

121
00:05:44,777 --> 00:05:47,046
onto the surface
of this boulder.

122
00:05:47,079 --> 00:05:50,015
And I lead the team that's
developing these grippers.

123
00:05:50,048 --> 00:05:52,952
First, we'll grab onto
the outside of the rock

124
00:05:52,985 --> 00:05:55,621
and then use that grip
to support a drill

125
00:05:55,654 --> 00:05:58,424
that penetrates into the rock
about four or five inches,

126
00:05:58,457 --> 00:06:00,793
which creates a really
strong anchor point

127
00:06:00,826 --> 00:06:03,262
to pull that boulder
off the surface.

128
00:06:03,295 --> 00:06:06,232
Now the boulder has a
mass of about 20 tons,

129
00:06:06,265 --> 00:06:09,301
but on an asteroid, it only
weighs one or two pounds,

130
00:06:09,334 --> 00:06:11,003
and that's because the
gravitational environment

131
00:06:11,036 --> 00:06:11,871
is so low.

132
00:06:13,272 --> 00:06:15,941
So we're actually more worried
about forces like cohesion

133
00:06:15,974 --> 00:06:18,277
between the regolith
and the boulder

134
00:06:18,310 --> 00:06:22,181
than we are about the
weight of that boulder.

135
00:06:22,214 --> 00:06:23,916
Once we have it back
off the surface,

136

00:06:23,949 --> 00:06:25,684
we're gonna wrap it up tight
so we can bring it back

137
00:06:25,717 --> 00:06:27,186
to the Earth-Moon System.

138
00:06:27,219 --> 00:06:28,587
We're gonna do some
other cool things with it

139
00:06:28,620 --> 00:06:31,124
before we depart the asteroid.

140
00:06:32,157 --> 00:06:34,693
So the high-level goals for ARM.

141
00:06:34,726 --> 00:06:36,962
The first one, is
demonstrate the ability

142
00:06:36,995 --> 00:06:39,999
to alter an
asteroid's trajectory.

143
00:06:40,032 --> 00:06:42,435
So nudge it out of the way
if it's coming to hit Earth,

144
00:06:42,468 --> 00:06:43,903
so it's a near miss instead of

145
00:06:43,936 --> 00:06:46,972
a dinosaur killing
kind of event.

146
00:06:47,005 --> 00:06:48,874
The second one is
to get that boulder.

147
00:06:48,907 --> 00:06:52,178
And we're gonna put that
boulder in orbit around the Moon

148
00:06:52,211 --> 00:06:54,747
where it's safe and it doesn't
risk any damage to the Earth

149
00:06:54,780 --> 00:06:57,349
or any of our assets
in Earth orbit,

150
00:06:57,382 --> 00:06:59,318
but where it's
accessible to astronauts

151
00:06:59,351 --> 00:07:02,655
in a follow-on mission and
potentially others, as well.

152
00:07:02,688 --> 00:07:04,323
You may have heard about
some of these companies

153
00:07:04,356 --> 00:07:07,860
that have started up recently
trying to mine asteroids.

154
00:07:07,893 --> 00:07:09,595
We might make that
boulder available to them

155
00:07:09,628 --> 00:07:13,766
as sort of a practice
resource close to home.

156
00:07:13,799 --> 00:07:17,136
The third key goal is to
demonstrate technologies

157
00:07:17,169 --> 00:07:19,305
for NASA's Journey to Mars.

158
00:07:19,338 --> 00:07:22,308
The Journey to Mars is
NASA's plan to send humans

159
00:07:22,341 --> 00:07:27,279
to the surface of Mars in
the late 2030s or 2040s.

160
00:07:27,312 --> 00:07:29,682
To do that, we need a
few key technologies

161
00:07:29,715 --> 00:07:31,250
we don't have today.

162
00:07:31,283 --> 00:07:33,452
One of those is the
SEP, the ability to push

163
00:07:33,485 --> 00:07:35,788
those heavy things
around the solar system.

164
00:07:35,821 --> 00:07:39,124
This would be habitats,
fuel, a rocket

165
00:07:39,157 --> 00:07:42,428
to get us back off the
surface of Mars, food, water.

166
00:07:42,461 --> 00:07:44,930
We wanna stage all of that
at Mars before we ever

167
00:07:44,963 --> 00:07:48,300

send a crew out there,
and we need this

168
00:07:48,333 --> 00:07:50,302
high-power SEP to get it there.

169
00:07:50,335 --> 00:07:52,438
We'll also demonstrate robotics.

170
00:07:52,471 --> 00:07:55,307
Any human mission to Mars
is gonna be a collaboration

171
00:07:55,340 --> 00:07:57,910
between robots and astronauts.

172
00:07:57,943 --> 00:08:01,013
And so, we'll take the
first steps in that here.

173
00:08:01,046 --> 00:08:04,650
And in the follow-on
mission, ARCM,

174
00:08:04,683 --> 00:08:06,785
the Asteroid Redirect
Crewed Mission,

175
00:08:06,818 --> 00:08:09,455
we'll be doing EVAs
at the boulder.

176
00:08:09,488 --> 00:08:11,824
The first time doing
astronaut activities

177
00:08:11,857 --> 00:08:15,594
beyond low Earth orbit
since the days of Apollo.

178
00:08:15,627 --> 00:08:17,396
And we would use
the Orion spacecraft

179
00:08:17,429 --> 00:08:19,765
and the SLS rocket for that.

180
00:08:21,600 --> 00:08:22,835
So the first one of those goals

181
00:08:22,868 --> 00:08:24,537
always gets the
attention, right?

182
00:08:24,570 --> 00:08:26,305
We're gonna push an
asteroid out of the way

183
00:08:26,338 --> 00:08:28,007
so it doesn't hit the Earth.

184
00:08:28,040 --> 00:08:31,777
So I got some of my jokes
from the popular media,

185
00:08:31,810 --> 00:08:33,479
and here you can see,
we've already had

186
00:08:33,512 --> 00:08:35,614
our get out of jail free card.

187
00:08:35,647 --> 00:08:37,816
The dinosaurs saved the mammals

188
00:08:37,849 --> 00:08:41,720
when the first extinction
event came along.

189
00:08:41,753 --> 00:08:44,056
The other one I like,
here are two dinosaurs

190
00:08:44,089 --> 00:08:47,526
sitting together, and in case
you can't read the bottom,

191
00:08:47,559 --> 00:08:50,996
one of them is saying,
"I'm saying now is the time

192
00:08:51,029 --> 00:08:53,666
to develop technology
to deflect an asteroid."

193
00:08:53,699 --> 00:08:54,700
(audience laughing)

194
00:08:54,733 --> 00:08:56,903
So, I couldn't agree more.

195
00:08:58,670 --> 00:09:02,408
Now, some of you may have said,
I've seen this movie before.

196
00:09:02,441 --> 00:09:04,810
What's scary is the interns
that we get into our lab,

197
00:09:04,843 --> 00:09:06,312
some of them haven't
seen this movie,

198
00:09:06,345 --> 00:09:07,179
and they don't remember it.

199
00:09:07,212 --> 00:09:08,547
(audience laughing)

200
00:09:08,580 --> 00:09:09,949
But we send Bruce Willis, right?

201
00:09:09,982 --> 00:09:12,051
If an asteroid is
coming to hit the Earth,

202
00:09:12,084 --> 00:09:14,153
put a nuclear bomb
on the surface

203
00:09:14,186 --> 00:09:16,088
and obliterate
it, right?

204
00:09:16,121 --> 00:09:18,624
And that's one possible method.

205
00:09:18,657 --> 00:09:20,926
And if it was
coming really fast,

206
00:09:20,959 --> 00:09:22,661
and we didn't have
a lot of time,

207
00:09:22,694 --> 00:09:25,664
that might be the
method that we chose.

208
00:09:25,697 --> 00:09:27,466
But there's actually
several other ways

209
00:09:27,499 --> 00:09:30,569
that we might deflect
that asteroid.

210

00:09:30,602 --> 00:09:32,838
And some of them don't require
launching a nuclear bomb

211
00:09:32,871 --> 00:09:34,941
off the coast of Florida.

212
00:09:36,508 --> 00:09:39,678
The method we've selected is
a gravity tractor technique.

213
00:09:39,711 --> 00:09:42,181
We're not sure if it's
the best technique.

214
00:09:42,214 --> 00:09:44,283
We don't know, we haven't
done this before, right?

215
00:09:44,316 --> 00:09:45,818
But it's the technique we think

216
00:09:45,851 --> 00:09:47,820
we can achieve
with this mission,

217
00:09:47,853 --> 00:09:50,923
and so we collect that
boulder, and the combined mass

218
00:09:50,956 --> 00:09:53,425
of the spacecraft and
the boulder is enough

219
00:09:53,458 --> 00:09:56,061
that when we hover
in a halo orbit

220
00:09:56,094 --> 00:09:58,764
on one side of the asteroid,

the gravitational attraction

221
00:09:58,797 --> 00:10:01,767
between us and that
parent asteroid

222
00:10:01,800 --> 00:10:05,237
will slowly tug it, over the
course of several months,

223
00:10:05,270 --> 00:10:06,939
and change its orbit.

224
00:10:06,972 --> 00:10:10,442
So we're tracking all of the
potentially hazardous asteroids

225
00:10:10,475 --> 00:10:12,077
that are gonna come
and hit the Earth.

226
00:10:12,110 --> 00:10:13,545
By the way, nothing
to worry about

227
00:10:13,578 --> 00:10:17,683
for the next 50 to 100 years,
but we're tracking them.

228
00:10:17,716 --> 00:10:20,452
And so we could send one of
these missions out in advance,

229
00:10:20,485 --> 00:10:22,888
demonstrate that we've
pushed it off course,

230
00:10:22,921 --> 00:10:25,524
and then continue to track
it to confirm that it is,

231
00:10:25,557 --> 00:10:27,893
in fact, no longer a threat.

232
00:10:30,729 --> 00:10:33,132
So to get that boulder,
to increase our mass,

233
00:10:33,165 --> 00:10:35,901
to make that gravity
tractor extra effective,

234
00:10:35,934 --> 00:10:37,569
we're gonna use these grippers.

235
00:10:37,602 --> 00:10:41,774
So two of these grippers
that are about yea big

236
00:10:41,807 --> 00:10:44,610
are gonna grab that big
boulder you see in the back.

237
00:10:44,643 --> 00:10:47,546
And that's a mock up that's
at the Satellite Servicing Lab

238
00:10:47,579 --> 00:10:50,215
out at Goddard
Space Flight Center.

239
00:10:50,248 --> 00:10:52,418
So how do you grab a rock?

240
00:10:53,618 --> 00:10:56,488
We use a technology
called microspines.

241
00:10:56,521 --> 00:10:58,057

They're basically sharp hooks

242
00:10:58,090 --> 00:11:00,292
and flexible
suspension structures.

243
00:11:00,325 --> 00:11:02,227
So you drag them
along the surface,

244
00:11:02,260 --> 00:11:04,697
and they opportunistically
catch hold

245
00:11:04,730 --> 00:11:07,833
of bumps, pits,
ledges, ramps, holes.

246
00:11:08,934 --> 00:11:11,103
They only need really
small roughness.

247
00:11:11,136 --> 00:11:14,339
Much smaller than what you
might grip with your hand.

248
00:11:14,372 --> 00:11:16,508
In fact, in these prototypes,
we're using fishhooks.

249
00:11:16,541 --> 00:11:18,143
So you can imagine
dragging a sharp fishhook

250
00:11:18,176 --> 00:11:21,580
across a rock, it's gonna
catch pretty readily.

251
00:11:21,613 --> 00:11:23,315
A key feature of

these microspines,

252
00:11:23,348 --> 00:11:25,951
is that when they catch, they
don't prevent their neighbors

253
00:11:25,984 --> 00:11:29,588
from also trying to search
out a good place to catch.

254
00:11:29,621 --> 00:11:31,123
So they load share.

255
00:11:31,156 --> 00:11:33,892
Each microspine only holds
one or two pounds of force,

256
00:11:33,925 --> 00:11:35,961
but you can use them
by the thousands,

257
00:11:35,994 --> 00:11:40,166
and only need 10% or so to
support a really large load.

258
00:11:43,101 --> 00:11:44,737
So here's what one
of those looks like

259
00:11:44,770 --> 00:11:46,972
as it drags across the surface.

260
00:11:47,005 --> 00:11:49,775
You can see the hook
catches, and when it catches,

261
00:11:49,808 --> 00:11:52,578
you'll notice the yellow sort
of rubber band-like feature

262
00:11:52,611 --> 00:11:54,246
in the back stretches out.

263
00:11:54,279 --> 00:11:57,049
That's when it's supporting
that one or two pounds of force.

264
00:11:57,082 --> 00:12:00,119
And again, we only need
10% or so of these to catch

265
00:12:00,152 --> 00:12:04,390
in order to support the loads
we need for the mission.

266
00:12:08,593 --> 00:12:12,765
So in order to grab a rock, we
need more than just that tip.

267
00:12:14,132 --> 00:12:17,503
Rocks are rough on a macro
scale as well as a micro scale,

268
00:12:17,536 --> 00:12:20,339
and so we use a
hierarchical compliance

269
00:12:20,372 --> 00:12:22,875
to try and conform to
the rock's geometry

270
00:12:22,908 --> 00:12:25,677
at all of the different
length scales.

271
00:12:25,710 --> 00:12:27,713
And since we're doing
this in microgravity,

272

00:12:27,746 --> 00:12:30,082
we use oppositional microspines.

273
00:12:30,115 --> 00:12:32,117
So they're reacting
against one another,

274
00:12:32,150 --> 00:12:33,886
they're all squeezing
towards the center,

275
00:12:33,919 --> 00:12:36,922
so that you don't need any
gravity to load them up.

276
00:12:36,955 --> 00:12:38,524
And they can support forces

277
00:12:38,557 --> 00:12:41,894
that you might exert in
any different direction.

278
00:12:41,927 --> 00:12:43,362
And, of course, since
we're going to an asteroid,

279
00:12:43,395 --> 00:12:45,898
we better make sure
that they can withstand

280
00:12:45,931 --> 00:12:48,000
the extreme environment
that we're gonna find there.

281
00:12:48,033 --> 00:12:49,268
So this is vacuum,

282
00:12:49,301 --> 00:12:51,770
potentially very cold
temperatures, as well.

283
00:12:51,803 --> 00:12:54,072
So those rubber band-like
features I showed you before,

284
00:12:54,105 --> 00:12:55,541
those are not gonna work.

285
00:12:55,574 --> 00:12:57,743
So we've done a
lot of development

286
00:12:57,776 --> 00:13:00,045
to make metallic
versions of microspines

287
00:13:00,078 --> 00:13:04,049
that can withstand
those cold temperatures.

288
00:13:04,082 --> 00:13:06,518
On the first point, the
hierarchical compliance,

289
00:13:06,551 --> 00:13:09,988
most natural surfaces
have fractal roughness,

290
00:13:10,021 --> 00:13:13,258
meaning they're rough at every
length scale you look at.

291
00:13:13,291 --> 00:13:15,427
So as you continue to
increase your magnification

292
00:13:15,460 --> 00:13:17,095
with the microscope, all you see

293

00:13:17,128 --> 00:13:19,464
is the same level of roughness.

294
00:13:19,497 --> 00:13:22,467
So to match that, we use
a hierarchical system

295
00:13:22,500 --> 00:13:26,004
that can conform at all of
those different length scales.

296
00:13:26,037 --> 00:13:28,807
So the microspines grip
at the milometer scale,

297
00:13:28,840 --> 00:13:32,277
we put those into cassettes
that can conform to the rock

298
00:13:32,310 --> 00:13:35,814
at centimeter scale, and we use
the robotic arms to place us

299
00:13:35,847 --> 00:13:38,383
in position at the
10 centimeter,

300
00:13:38,416 --> 00:13:41,386
100 centimeter scale.

301
00:13:41,419 --> 00:13:43,255
So you can see that in action.

302
00:13:43,288 --> 00:13:46,325
Here, you've seen some of
these microspines have caught,

303
00:13:46,358 --> 00:13:48,360
they've stretched out,
they're sharing the load

304
00:13:48,393 --> 00:13:51,263
between any of them that
have stretched out here.

305
00:13:51,296 --> 00:13:53,999
Let's see, you can
see these have caught.

306
00:13:54,032 --> 00:13:55,934
And then these here
have not caught.

307
00:13:55,967 --> 00:13:59,905
So this is more than 10%,
we have a very good grip.

308
00:13:59,938 --> 00:14:03,508
You can see here, some of that
centimeter scale compliance.

309
00:14:03,541 --> 00:14:07,179
Some of these cassettes have
gone to different angles

310
00:14:07,212 --> 00:14:08,614
to conform to the
rock, and some of them

311
00:14:08,647 --> 00:14:12,618
have squeezed in
closer to the gripper.

312
00:14:12,651 --> 00:14:15,320
Another demonstration, you
can see both of those levels

313
00:14:15,353 --> 00:14:18,891
happening here and
supporting some force.

314
00:14:18,924 --> 00:14:23,395
So this is about 25 pounds,
30 pounds on the left and

315
00:14:23,428 --> 00:14:27,600
20 pounds on the right with
some of our early prototypes.

316
00:14:28,967 --> 00:14:30,802
Here's a video that's
showing you how that works.

317
00:14:30,835 --> 00:14:33,205
We have two actuations,

318
00:14:33,238 --> 00:14:35,407
two mechanisms that
are at play here.

319
00:14:35,440 --> 00:14:38,143
One that puts those
cassettes up and down,

320
00:14:38,176 --> 00:14:41,346
and the other one that squeezes
them in towards the center.

321
00:14:41,379 --> 00:14:43,382
So the idea is, you
come into the rock,

322
00:14:43,415 --> 00:14:45,884
you deploy your microspines,
they all conform

323
00:14:45,917 --> 00:14:49,154
to whatever roughness they
find, you squeeze together,

324
00:14:49,187 --> 00:14:51,590
and now you've got a good grip.

325
00:14:51,623 --> 00:14:53,892
You just reverse that
process to let go.

326
00:14:53,925 --> 00:14:56,195
So it's a reusable gripper.

327
00:14:58,029 --> 00:14:59,364
Here's some of the
work we've been doing

328
00:14:59,397 --> 00:15:02,501
to make these
microspines space-grade.

329
00:15:02,534 --> 00:15:04,102
You can see some of
the early prototypes

330
00:15:04,135 --> 00:15:05,871
in the upper left when
we are using those

331
00:15:05,904 --> 00:15:08,974
rubber band-like
polyurethane flexures.

332
00:15:09,007 --> 00:15:11,343
We used some extension
springs, they kind of thing

333
00:15:11,376 --> 00:15:13,979
you would find in a ballpoint
pen, and then we used

334
00:15:14,012 --> 00:15:16,481

these sort of curly Q flexures
where we started using

335
00:15:16,514 --> 00:15:20,119
the aluminum itself as
the spring material.

336
00:15:21,286 --> 00:15:22,421
If you look in the
center, you can see

337
00:15:22,454 --> 00:15:24,790
we went to sort of
zig-zag like flexures.

338
00:15:24,823 --> 00:15:28,060
And on the right, we've actually
been gluing in very thin

339
00:15:28,093 --> 00:15:31,496
steel ribbons that are acting
like a leaf spring to provide

340
00:15:31,529 --> 00:15:35,200
that compliance, mimicking
what the rubber band does.

341
00:15:35,233 --> 00:15:37,235
In the lower left,
we've been experimenting

342
00:15:37,268 --> 00:15:39,271
with different kinds of hooks.

343
00:15:39,304 --> 00:15:42,374
So we have a fish hook,
which is a conical point,

344
00:15:42,407 --> 00:15:44,776
we've also been looking at

razor blades, so more of

345
00:15:44,809 --> 00:15:48,981
a shovel tip, and some more
exotic things even than that.

346
00:15:50,382 --> 00:15:52,584
These are now being
carried on a linkage.

347
00:15:52,617 --> 00:15:54,720
And here you can see some
of this iterative design

348
00:15:54,753 --> 00:15:56,254
I mentioned at the beginning.

349
00:15:56,287 --> 00:15:59,224
We've gone through about four
different linkage topologies

350
00:15:59,257 --> 00:16:03,295
with multiple designs at
each one of those iterations.

351
00:16:03,328 --> 00:16:04,930
And we're trying to make
sure that the microspines

352
00:16:04,963 --> 00:16:07,966
all make contact with the
rock, and that as we drag them

353
00:16:07,999 --> 00:16:11,136
along the surface, the angle
doesn't change too much.

354
00:16:11,169 --> 00:16:12,237
And that's true whether we're on

355
00:16:12,270 --> 00:16:14,773
a flat rock or a round rock.

356
00:16:14,806 --> 00:16:16,208
So we've been
playing around with

357
00:16:16,241 --> 00:16:19,311
the four-bar linkage perimeters
to try and optimize that.

358
00:16:19,344 --> 00:16:21,513
But you can't just
build the prototype,

359
00:16:21,546 --> 00:16:23,181
you have to test the prototype.

360
00:16:23,214 --> 00:16:26,651
And so here is a test stand
for a single cassette.

361
00:16:26,684 --> 00:16:28,520
We're able to execute a motion

362
00:16:28,553 --> 00:16:31,757
where we bring those
microspines into the rock,

363
00:16:31,790 --> 00:16:33,258
drag them along the surface,

364
00:16:33,291 --> 00:16:37,429
and there's a six axis force
torque censor behind the rock.

365
00:16:37,462 --> 00:16:38,930
So we're measuring
all of the forces

366
00:16:38,963 --> 00:16:42,034
during that whole procedure.

367
00:16:42,067 --> 00:16:44,636
I think there's a
video of this, yup.

368
00:16:44,669 --> 00:16:47,372
So here you go, this
is a very soft rock.

369
00:16:47,405 --> 00:16:49,674
We're going to a
carbonaceous chondrite,

370
00:16:49,707 --> 00:16:52,611
which is a type of asteroid
that is usually considered

371
00:16:52,644 --> 00:16:55,981
to be softer than the stony
asteroids, the S-types,

372
00:16:56,014 --> 00:16:58,750
or the metallic
asteroids, the M-types.

373
00:16:58,783 --> 00:17:00,819
But we chose a C-type asteroid

374
00:17:00,852 --> 00:17:03,055
because it has the
most water content.

375
00:17:03,088 --> 00:17:04,923
It has the most
carbon rich molecules.

376

00:17:04,956 --> 00:17:08,727
So it's scientifically
very interesting.

377
00:17:08,760 --> 00:17:12,664
In fact, some folks believe
that asteroid and comet impacts

378
00:17:12,697 --> 00:17:15,400
actually seeded the
primordial soup,

379
00:17:15,433 --> 00:17:18,136
put the building blocks
of life onto the planet

380
00:17:18,169 --> 00:17:19,805
during the late
bombardment period

381
00:17:19,838 --> 00:17:22,774
that helped spark
life on our planet.

382
00:17:22,807 --> 00:17:24,676
So we wanna investigate,
what are those carbon bearing

383
00:17:24,709 --> 00:17:27,112
molecules that are
on the surface

384
00:17:27,145 --> 00:17:28,914
of these C-type
asteroids?

385
00:17:28,947 --> 00:17:30,649
Now what you probably
can't see very well

386

00:17:30,682 --> 00:17:34,686
in the lower right corner
there is a plot of the forces.

387
00:17:34,719 --> 00:17:37,289
So during the drag force,
that blue line goes up

388
00:17:37,322 --> 00:17:40,525
because we're having a lot
of force along the surface.

389
00:17:40,558 --> 00:17:42,994
And then when we start
to raise the center,

390
00:17:43,027 --> 00:17:45,597
which is out of frame, you
see the red line go up,

391
00:17:45,630 --> 00:17:47,265
which is the adhesive
force we're getting

392
00:17:47,298 --> 00:17:49,868
pulling away from that rock.

393
00:17:49,901 --> 00:17:52,137
So we can use this
test stand to optimize

394
00:17:52,170 --> 00:17:55,941
both the microspine design
and that linkage design.

395
00:17:55,974 --> 00:17:58,276
And it sure beats making
a thousand microspines

396
00:17:58,309 --> 00:18:00,479

every time you
have a new design.

397
00:18:00,512 --> 00:18:02,914
But in order to estimate what
that grip strength would be,

398
00:18:02,947 --> 00:18:04,516
we do a statistically
method called

399
00:18:04,549 --> 00:18:07,352
a Monte Carlo simulation
to try and predict

400
00:18:07,385 --> 00:18:09,488
what a grip strength would be at

401
00:18:09,521 --> 00:18:12,858
out of a distribution
of 20 or so tests.

402
00:18:15,727 --> 00:18:16,895
Of course, every once
in a while,

403
00:18:16,928 --> 00:18:18,864
we do make a
full gripper.

404
00:18:18,897 --> 00:18:21,700
So this was a 2.0 gripper.

405
00:18:21,733 --> 00:18:25,403
It was worked on in
collaboration with Thomas Evans

406
00:18:25,436 --> 00:18:26,938
at West Virginia
University, who provided

407
00:18:26,971 --> 00:18:29,274
the robot arm to do testing.

408
00:18:29,307 --> 00:18:33,345
So this gripper has
about 650 microspines.

409
00:18:33,378 --> 00:18:35,380
It's got them in
two different rings,

410
00:18:35,413 --> 00:18:37,549
and it turns out that
was a bad design.

411
00:18:37,582 --> 00:18:40,752
So in the 3.0 gripper, we
went back to just one ring.

412
00:18:40,785 --> 00:18:42,320
The reason it was bad is
because the inner ring

413
00:18:42,353 --> 00:18:44,656
and the outer ring would
be at different angles

414
00:18:44,689 --> 00:18:47,425
if you were on a flat
rock versus a curved rock.

415
00:18:47,458 --> 00:18:50,162
And so the angles of those
hooks essentially meant one ring

416
00:18:50,195 --> 00:18:53,131
was very effective and the
other ring was not effective.

417
00:18:53,164 --> 00:18:56,301
So we just decided,
let's just pick one ring.

418
00:18:56,334 --> 00:18:58,870
You can see the same
kind of data coming in

419
00:18:58,903 --> 00:19:01,840
in the upper left as we're
starting to support loads.

420
00:19:01,873 --> 00:19:06,044
In this test, we get up to,
that's about 100, 120 newtons.

421
00:19:07,412 --> 00:19:10,916
Before you see us slip,
and then it reattaches

422
00:19:10,949 --> 00:19:13,051
and starts to grip again.

423
00:19:15,687 --> 00:19:17,055
A question we get all the time

424
00:19:17,088 --> 00:19:20,025
is what happens if there's
dust on the surface?

425
00:19:20,058 --> 00:19:22,327
And since the hooks
are very sharp,

426
00:19:22,360 --> 00:19:24,129
as long as that
dust isn't too deep,

427
00:19:24,162 --> 00:19:26,064

they'll just dig
right through it.

428
00:19:26,097 --> 00:19:28,633
And so here you can see a
prototype that was built,

429
00:19:28,666 --> 00:19:30,669
where we're able
to pull out a rock

430
00:19:30,702 --> 00:19:33,772
that is completely
covered in dust.

431
00:19:33,805 --> 00:19:35,307
And so on the asteroid
surface, it may be

432
00:19:35,340 --> 00:19:37,876
a dusty environment, but we
don't expect that dust layer

433
00:19:37,909 --> 00:19:42,080
to be so deep that we won't
just cut right through it.

434
00:19:43,948 --> 00:19:46,585
So some of the
prototype evolution.

435
00:19:46,618 --> 00:19:49,588
We started with rapid
prototype 3D printed parts,

436
00:19:49,621 --> 00:19:53,024
moving as fast as we could,
designing in plastic.

437
00:19:53,057 --> 00:19:55,026

And then we move into
the aluminum grippers,

438
00:19:55,059 --> 00:19:56,828
which are larger,
that's the actual size

439
00:19:56,861 --> 00:19:58,663
we're gonna fly on the mission.

440
00:19:58,696 --> 00:20:00,832
So we call this the 2.0 Tool.

441
00:20:00,865 --> 00:20:03,235
We actually built two of
those grippers at that size.

442
00:20:03,268 --> 00:20:06,705
So here's 2.1, has some
slightly different electronics

443
00:20:06,738 --> 00:20:10,275
and different microspines,
the hoop flexures down there

444
00:20:10,308 --> 00:20:13,979
where we were testing
out some new concepts.

445
00:20:14,012 --> 00:20:17,082
Currently, we're actually
building the 3.0 Tool.

446
00:20:17,115 --> 00:20:18,917
So this is coming
together right now.

447
00:20:18,950 --> 00:20:20,986
You're seeing pictures
hot off the presses.

448
00:20:21,019 --> 00:20:23,421
This is maybe a day or
two ago we took this one.

449
00:20:23,454 --> 00:20:25,423
This is our drivetrain.

450
00:20:25,456 --> 00:20:27,058
It's basically like the gearbox

451
00:20:27,091 --> 00:20:28,693
or the transmission in your car.

452
00:20:28,726 --> 00:20:30,295
It's got a two-stage clutch,

453
00:20:30,328 --> 00:20:34,199
and it powers six different
mechanisms in the Tool.

454
00:20:34,232 --> 00:20:37,002
The 3.0 Tool is actually
much more complex

455
00:20:37,035 --> 00:20:40,572
than the 2.0, 2.1, any
of the previous Tools

456
00:20:40,605 --> 00:20:43,308
because we've added a
rotary percussive drill

457
00:20:43,341 --> 00:20:44,676
down the center.

458
00:20:45,910 --> 00:20:49,848
Here's a underside view
of this drivetrain.

459
00:20:49,881 --> 00:20:51,616
And here's that drill.

460
00:20:51,649 --> 00:20:53,118
So it's a little
hard to make out

461
00:20:53,151 --> 00:20:55,186
everything that's going on,
but you've got things like

462
00:20:55,219 --> 00:20:57,122
you're chuck, which
is how you connect

463
00:20:57,155 --> 00:21:00,625
your drill bit to the drill,
a spindle, percussions,

464
00:21:00,658 --> 00:21:03,995
this is a hammer drill,
an anchor deployment,

465
00:21:04,028 --> 00:21:07,432
I'll talk about that in a little
bit, and a feed mechanism.

466
00:21:07,465 --> 00:21:09,334
And we're lucky, because
at JPL there's been a lot

467
00:21:09,367 --> 00:21:13,772
of development work already on
how to drill in outer space.

468
00:21:13,805 --> 00:21:15,707
So Curiosity, of
course, has a drill,

469
00:21:15,740 --> 00:21:18,743
a rotary percussive drill,
and the Mars 2020 mission,

470
00:21:18,776 --> 00:21:21,313
which is a bit ahead of us
in the development timeline,

471
00:21:21,346 --> 00:21:22,814
has also got a drill.

472
00:21:22,847 --> 00:21:25,617
So we've tried to leverage all
of the lessons that they've

473
00:21:25,650 --> 00:21:28,019
learned and all of the
design experience they have,

474
00:21:28,052 --> 00:21:31,556
incorporating those
things into our drill.

475
00:21:32,824 --> 00:21:35,026
Here's the Tool in
its current state

476
00:21:35,059 --> 00:21:36,628
as its getting assembled.

477
00:21:36,661 --> 00:21:39,064
So it's only the drill and
the drivetrain right now.

478
00:21:39,097 --> 00:21:42,267
The gripper is still
getting put together.

479
00:21:42,300 --> 00:21:45,270

But that drivetrain is really
complicated because we've made

480
00:21:45,303 --> 00:21:49,541
a choice not to fly motors
inside our Tool, but instead

481
00:21:49,574 --> 00:21:52,143
to use the motors that
are in the robotic arm

482
00:21:52,176 --> 00:21:54,245
to drive our Tool mechanically.

483
00:21:54,278 --> 00:21:56,247
So there's a tool drive output

484
00:21:56,280 --> 00:21:58,650
at the end of the robotic
arm, and we're using

485
00:21:58,683 --> 00:22:01,886
those outputs to
power our mechanisms.

486
00:22:01,919 --> 00:22:05,056
Trouble is, there's three
outputs on the robotic arm,

487
00:22:05,089 --> 00:22:08,393
two rotary and one linear,
and we have six mechanisms

488
00:22:08,426 --> 00:22:11,296
on our Tool that
we need to operate.

489
00:22:11,329 --> 00:22:13,965
But we don't have to operate
them all at the same time.

490
00:22:13,998 --> 00:22:15,533
So we use a clutch.

491
00:22:15,566 --> 00:22:17,535
Same way you don't
drive your car

492
00:22:17,568 --> 00:22:20,038
with all the gears
running simultaneously.

493
00:22:20,071 --> 00:22:22,240
We index between
whether we're gripping

494
00:22:22,273 --> 00:22:24,409
or drilling or anchoring.

495
00:22:24,442 --> 00:22:26,411
So this ended up
being pretty complex,

496
00:22:26,444 --> 00:22:30,515
but what I think is some
pretty beautiful hardware.

497
00:22:30,548 --> 00:22:32,016
I'm a mechanical
engineer, though.

498
00:22:32,049 --> 00:22:33,251
(audience laughing)

499
00:22:33,284 --> 00:22:36,054
So I like all these
kinds of pictures.

500
00:22:37,155 --> 00:22:39,424

Now with that drill,
our operations

501
00:22:39,457 --> 00:22:42,260
get a little bit more
complex, as well.

502
00:22:42,293 --> 00:22:45,163
So we allow the robotic arm
to bring us into contact

503
00:22:45,196 --> 00:22:47,599
with the surface and align
us, make sure our drill bit's

504
00:22:47,632 --> 00:22:51,669
facing orthogonally to
the rock wherever we are.

505
00:22:51,702 --> 00:22:54,506
And we deploy the gripper,
we bring those cassettes

506
00:22:54,539 --> 00:22:57,075
down onto the rock and
then squeeze them in

507
00:22:57,108 --> 00:22:59,911
to establish a grip with
all of the microspines.

508
00:22:59,944 --> 00:23:03,214
Once we've got that grip,
we're able to drill.

509
00:23:03,247 --> 00:23:05,283
The gripper is
basically there to react

510
00:23:05,316 --> 00:23:08,453

the forces and torques of
drilling in microgravity.

511
00:23:08,486 --> 00:23:11,322
An analogy I like to use is
if you're on an asteroid,

512
00:23:11,355 --> 00:23:14,025
and you've got your drill
that you use at home,

513
00:23:14,058 --> 00:23:17,228
if you push that drill bit into
the surface, on an asteroid,

514
00:23:17,261 --> 00:23:19,964
you're going to be pushing
yourself into outer space.

515
00:23:19,997 --> 00:23:22,867
And if you pull the trigger on
that drill to start drilling

516
00:23:22,900 --> 00:23:25,036
it gets worse, 'cause you're
gonna start spinning around

517
00:23:25,069 --> 00:23:26,538
(audience laughing)
the drill bit

518
00:23:26,571 --> 00:23:29,007
instead of the drill bit
spinning in the borehole.

519
00:23:29,040 --> 00:23:31,643
So we use a microspine
gripper to react those loads

520
00:23:31,676 --> 00:23:34,512

and make sure that the
drill goes into the rock

521
00:23:34,545 --> 00:23:36,414
and make sure it
spins and the robot

522
00:23:36,447 --> 00:23:38,883
and the spacecraft don't spin.

523
00:23:38,916 --> 00:23:40,652
So once we've drilled
to a certain depth,

524
00:23:40,685 --> 00:23:42,420
we do an anchoring process.

525
00:23:42,453 --> 00:23:45,423
We actually cut a groove in
the bottom of the borehole

526
00:23:45,456 --> 00:23:48,626
that locks us in
geometrically to the rock.

527
00:23:48,659 --> 00:23:51,529
So we do that by flanging
out some little cutters,

528
00:23:51,562 --> 00:23:53,331
and I'll show you a picture
of that in a second.

529
00:23:53,364 --> 00:23:56,167
But that creates a very strong
anchor that we're now able

530
00:23:56,200 --> 00:23:59,204
to pull on with thousands
of newtons of force

531
00:23:59,237 --> 00:24:02,541
to extract the boulder
off the surface.

532
00:24:03,774 --> 00:24:05,777
So of course we have
to prototype this.

533
00:24:05,810 --> 00:24:09,314
So we've put a drill down the
center of our 1.0 grippers,

534
00:24:09,347 --> 00:24:11,115
and because we are prototyping,

535
00:24:11,148 --> 00:24:14,953
we used the best, quickest,
dirtiest drill we could find,

536
00:24:14,986 --> 00:24:16,154
which was at Home Depot,

537
00:24:16,187 --> 00:24:18,356
it was a Bosch Rotary
Percussive Drill.

538
00:24:18,389 --> 00:24:21,659
We chopped it up, put the
innards into our own motor,

539
00:24:21,692 --> 00:24:23,595
and then had a prototype working

540
00:24:23,628 --> 00:24:25,763
where we were practicing
drilling into rock

541
00:24:25,796 --> 00:24:28,166

I think within about one summer.

542
00:24:28,199 --> 00:24:30,835
You can see on the right,
it's actually anchored itself

543
00:24:30,868 --> 00:24:32,504
to the ceiling, and is not only

544
00:24:32,537 --> 00:24:34,706
supporting the weight
of that whole assembly,

545
00:24:34,739 --> 00:24:36,641
but is also drilling
into the ceiling.

546
00:24:36,674 --> 00:24:38,776
So it's supporting
the loads it takes

547
00:24:38,809 --> 00:24:40,979
to drill into the ceiling.

548
00:24:42,813 --> 00:24:45,783
Now that's a harder than zero
G test going into the ceiling.

549
00:24:45,816 --> 00:24:48,119
Microgravity is
actually true zero G.

550
00:24:48,152 --> 00:24:50,555
So what we did was
fly on the Vomit Comet

551
00:24:50,588 --> 00:24:52,457
and test this mechanism.

552

00:24:52,490 --> 00:24:56,427
Now show of hands, who's
heard of the Vomit Comet?

553
00:24:56,460 --> 00:24:58,129
All right, that's
about three quarters,

554
00:24:58,162 --> 00:25:00,665
that's a good audience,
you guys are well-educated.

555
00:25:00,698 --> 00:25:02,800
For those that don't
know, it's an airplane

556
00:25:02,833 --> 00:25:06,804
that NASA operates that
flies a parabolic trajectory.

557
00:25:06,837 --> 00:25:09,674
So basically, the airplane
throws you up into the air

558
00:25:09,707 --> 00:25:12,844
and then tracks you
as you're in freefall,

559
00:25:12,877 --> 00:25:16,548
as you're experiencing zero
G as you would in space,

560
00:25:16,581 --> 00:25:19,417
and then you go into a nosedive,
and at the last second,

561
00:25:19,450 --> 00:25:22,186
they pull out of that
parabolic trajectory,

562

00:25:22,219 --> 00:25:24,589
they basically catch
you, and you experience

563
00:25:24,622 --> 00:25:27,492
double gravity for
the rest of that,

564
00:25:27,525 --> 00:25:29,360
the bottom part of the parabola,

565
00:25:29,393 --> 00:25:30,795
and then they go right
into the next one

566
00:25:30,828 --> 00:25:32,463
and just throw you
in the air again.

567
00:25:32,496 --> 00:25:35,300
So you get about 20 or
25 seconds of zero G,

568
00:25:35,333 --> 00:25:37,602
where you're floating
around, it's very zen.

569
00:25:37,635 --> 00:25:40,138
People ask if it's like a
roller coaster, it's not.

570
00:25:40,171 --> 00:25:42,206
It's very calm.

571
00:25:42,239 --> 00:25:44,576
But then when they catch you,
and you go into double gravity

572
00:25:44,609 --> 00:25:46,711
and you're glued down

against the floor,

573
00:25:46,744 --> 00:25:49,347
that feels a little bit
more like a roller coaster.

574
00:25:49,380 --> 00:25:51,316
And they give you very strong
motion sickness medication

575
00:25:51,349 --> 00:25:53,651
so that you don't
have the effect

576
00:25:53,684 --> 00:25:56,020
after which the plane is named.

577
00:25:56,053 --> 00:25:58,022
(audience laughing)

578
00:25:58,055 --> 00:26:00,058
So what you see here
is our prototype.

579
00:26:00,091 --> 00:26:01,960
It's on a Stewart Platform.

580
00:26:01,993 --> 00:26:03,294
And that Stewart Platform is on

581
00:26:03,327 --> 00:26:05,196
air bearings that have brakes.

582
00:26:05,229 --> 00:26:08,733
So basically the whole drill
and the rock float during

583
00:26:08,766 --> 00:26:11,869
the zero G portion, but when

we go into the two G portion,

584
00:26:11,902 --> 00:26:14,839
those brakes seize up and
lock everything in place.

585
00:26:14,872 --> 00:26:17,875
So it's a way for us to
not have our hardware

586
00:26:17,908 --> 00:26:21,112
crash into the floor every
one of those parabolas.

587
00:26:21,145 --> 00:26:23,815
And by the way, on a single
flight, they do 40 of those

588
00:26:23,848 --> 00:26:28,019
back to back, takes about
an hour, and it's exciting.

589
00:26:29,420 --> 00:26:32,523
We've done, I've done
now, 12 of these flights.

590
00:26:32,556 --> 00:26:35,159
So I have just over an
hour of zero G time.

591
00:26:35,192 --> 00:26:37,428
So if I keep up this pace,

592
00:26:37,461 --> 00:26:39,430
I'll never catch up
to the astronauts.

593
00:26:39,463 --> 00:26:40,465
(audience laughing)

594
00:26:40,498 --> 00:26:41,966
It's always fun.

595
00:26:41,999 --> 00:26:44,002
Now this is my favorite
video for another reason.

596
00:26:44,035 --> 00:26:45,770
You see all the
debris coming out.

597
00:26:45,803 --> 00:26:48,039
This is my favorite video
I'm going to show all night.

598
00:26:48,072 --> 00:26:50,475
But sort of for nerdy reasons.

599
00:26:50,508 --> 00:26:53,344
You see all that debris coming
out, and that's a barometer

600
00:26:53,377 --> 00:26:57,015
to tell what part of the
spacecraft a person works on.

601
00:26:57,048 --> 00:26:59,317
So if you show this to
robotics people, they're like,

602
00:26:59,350 --> 00:27:01,619
ah, this is awesome,
that's so cool.

603
00:27:01,652 --> 00:27:02,620
And you know that
they're used to

604
00:27:02,653 --> 00:27:04,555

interacting with the surface.

605
00:27:04,588 --> 00:27:06,991
If you show it to someone,
and they have very pale face

606
00:27:07,024 --> 00:27:09,694
and start to shake, you
know that they work on

607
00:27:09,727 --> 00:27:13,998
camera systems or remote
sensing or they have delicate

608
00:27:14,031 --> 00:27:18,102
equipment that's back at the
backside of the spacecraft.

609
00:27:18,135 --> 00:27:21,139
So on the actual asteroid
mission, we'll have a shroud.

610
00:27:21,172 --> 00:27:22,740
We'll make sure we
catch all of this debris

611
00:27:22,773 --> 00:27:24,242
so that it doesn't contaminate

612
00:27:24,275 --> 00:27:27,545
all of the other activities
we're going to be doing.

613
00:27:27,578 --> 00:27:30,281
Now the final reason I
think this is so cool,

614
00:27:30,314 --> 00:27:32,583
is you can see that
dust cloud kind of shift

615
00:27:32,616 --> 00:27:35,620
a couple of times
during the video, right?

616
00:27:35,653 --> 00:27:37,355
And this is, I didn't know this

617
00:27:37,388 --> 00:27:39,057
until I saw this video
and asked the question,

618
00:27:39,090 --> 00:27:42,860
I thought a computer was
flying this, the airplane.

619
00:27:42,893 --> 00:27:46,030
Turns out it's actually the
blue suiters, the pilots,

620
00:27:46,063 --> 00:27:48,266
who are manually steering,
trying to keep you

621
00:27:48,299 --> 00:27:50,835
in that sweet spot of zero G.

622
00:27:50,868 --> 00:27:54,972
And so every time you see that
dust cloud change directions,

623
00:27:55,005 --> 00:27:56,808
they're making a
small adjustment,

624
00:27:56,841 --> 00:27:59,777
trying to keep the plane
in that perfect freefall.

625

00:27:59,810 --> 00:28:02,880
So it might be .01
G, minus .02 G,

626
00:28:02,913 --> 00:28:05,883
and they're actually very
talented at keeping you

627
00:28:05,916 --> 00:28:08,953
in that perfect zone
throughout the 20, 25 seconds

628
00:28:08,986 --> 00:28:11,990
that you have to
do your experiment.

629
00:28:13,390 --> 00:28:15,493
So a little bit more about
the anchoring drill bit.

630
00:28:15,526 --> 00:28:16,728
That's a prototype on the right

631
00:28:16,761 --> 00:28:19,764
that we test in
pre-drilled boreholes.

632
00:28:19,797 --> 00:28:22,233
So we drill with a commercial
drill, we put this prototype

633
00:28:22,266 --> 00:28:26,104
in, and then practice the
anchoring procedure only.

634
00:28:26,137 --> 00:28:30,108
And you can see in the
colorful diagrams there

635
00:28:30,141 --> 00:28:32,944

how those anchoring
teeth flare out.

636
00:28:32,977 --> 00:28:34,812
And so this happens at
the bottom of the borehole

637
00:28:34,845 --> 00:28:36,581
as you're still
spinning the drill,

638
00:28:36,614 --> 00:28:39,183
but you're not pushing
the drill in any further.

639
00:28:39,216 --> 00:28:43,020
And so what you're left
with is a little groove.

640
00:28:43,053 --> 00:28:44,655
I hope you can see this one.

641
00:28:44,688 --> 00:28:45,890
A groove in the rock

642
00:28:45,923 --> 00:28:49,494
that you can pull on
with a lot of force.

643
00:28:49,527 --> 00:28:52,563
So here you can see again where
we've cut one of these open.

644
00:28:52,596 --> 00:28:54,732
You can see where
that groove was cut

645
00:28:54,765 --> 00:28:56,868
and where those teeth
were actually pulling.

646
00:28:56,901 --> 00:28:58,469
So we've been able to pull
on some of these rocks

647
00:28:58,502 --> 00:29:00,738
up to a few thousand pounds.

648
00:29:00,771 --> 00:29:03,708
And we've tested on all
different kinds of rocks.

649
00:29:03,741 --> 00:29:05,610
Because we've never been to
the surface of an asteroid,

650
00:29:05,643 --> 00:29:08,613
we don't actually have a
very good understanding

651
00:29:08,646 --> 00:29:11,682
of the strength of the boulders
that we're gonna find there.

652
00:29:11,715 --> 00:29:14,352
So we have meteorite data
and we have bolide data,

653
00:29:14,385 --> 00:29:17,655
which is measurements when
asteroids hit the atmosphere

654
00:29:17,688 --> 00:29:19,423
at what point they break up.

655
00:29:19,456 --> 00:29:21,626
And from those two sources
we can make some guesses

656

00:29:21,659 --> 00:29:24,829
about how strong the
rocks are on an asteroid

657
00:29:24,862 --> 00:29:27,565
and specifically on
a C-type asteroid.

658
00:29:27,598 --> 00:29:30,701
But the range is pretty big,
like two orders of magnitude.

659
00:29:30,734 --> 00:29:34,806
So we have to design
a very robust tool.

660
00:29:34,839 --> 00:29:36,908
Now it's gonna seem
like I'm kind of

661
00:29:36,941 --> 00:29:39,310
cutting this portion
of the talk short,

662
00:29:39,343 --> 00:29:41,179
and that's because it's
a work in progress.

663
00:29:41,212 --> 00:29:42,647
So you've literally
seen all the way

664
00:29:42,680 --> 00:29:44,849
up to where we are today.

665
00:29:44,882 --> 00:29:47,652
We're planning towards
a launch in 2021.

666
00:29:47,685 --> 00:29:49,187

So if you keep
following the news,

667
00:29:49,220 --> 00:29:51,589
you're gonna see a lot
more about the ARM Mission,

668
00:29:51,622 --> 00:29:53,391
Asteroid Redirect
Mission, and you'll

669
00:29:53,424 --> 00:29:57,228
see all of our good
results from that 3.0 Tool.

670
00:29:57,261 --> 00:30:00,097
But now we'll move into the
second phase of the talk.

671
00:30:00,130 --> 00:30:02,133
Second chapter,
we'll look at some

672
00:30:02,166 --> 00:30:04,268
rock climbing robots
that we've built.

673
00:30:04,301 --> 00:30:06,404
So on the right, that's
Christine Fuller and I

674
00:30:06,437 --> 00:30:09,640
out at the Mojave Desert
climbing in some lava tubes,

675
00:30:09,673 --> 00:30:11,910
place called Pisgah Crater.

676
00:30:13,143 --> 00:30:15,980
Here's our rock climbing

robot, and people ask,

677
00:30:16,013 --> 00:30:17,615
why would you want a
rock climbing robot,

678
00:30:17,648 --> 00:30:19,350
except that it's super awesome.

679
00:30:19,383 --> 00:30:21,018
(audience laughing)

680
00:30:21,051 --> 00:30:22,620
It turns out that there
are a lot of places

681
00:30:22,653 --> 00:30:26,257
on Mars and other planets
that we can't access with the

682
00:30:26,290 --> 00:30:29,894
six-wheeled rocker-bogie
rovers that we have now.

683
00:30:29,927 --> 00:30:33,231
So we see stratified
layers in the rock

684
00:30:33,264 --> 00:30:36,400
on outcrops on Mars, but
we can't get to them.

685
00:30:36,433 --> 00:30:38,002
We've tried, actually,
but because the rovers

686
00:30:38,035 --> 00:30:41,072
can only drive on a 20,
maybe 30 degree slope,

687
00:30:41,105 --> 00:30:43,441
we can't actually
access those outcrops.

688
00:30:43,474 --> 00:30:45,543
And if anyone's been
to the Grand Canyon,

689
00:30:45,576 --> 00:30:47,345
you see those different
layers, and they tell you,

690
00:30:47,378 --> 00:30:49,347
oh, you can look back in time

691
00:30:49,380 --> 00:30:51,148
by looking at the
different layers, right?

692
00:30:51,181 --> 00:30:53,050
The oldest ones
being at the bottom.

693
00:30:53,083 --> 00:30:55,486
So that's true on Mars, as
well, and wouldn't it be great

694
00:30:55,519 --> 00:30:58,956
to deploy instruments at all
of those different epochs

695
00:30:58,989 --> 00:31:02,226
in Mars's geologic
evolution and learn about

696
00:31:02,259 --> 00:31:03,794
the history of the planet?

697
00:31:03,827 --> 00:31:06,464

And it would be great,
and we hope to do that,

698
00:31:06,497 --> 00:31:11,235
but we can't do it with the
rovers that we have today.

699
00:31:11,268 --> 00:31:12,637
So the start of
rock climbing robot

700
00:31:12,670 --> 00:31:15,907
actually predates
me joining JPL.

701
00:31:15,940 --> 00:31:18,075
I was in graduate
school at Stanford,

702
00:31:18,108 --> 00:31:20,311
and we were working on
vertical climbing robots

703
00:31:20,344 --> 00:31:23,347
actually for the military
to try and climb up

704
00:31:23,380 --> 00:31:25,750
the outsides of brick buildings.

705
00:31:25,783 --> 00:31:28,252
So this robot was made
by Boston Dynamics.

706
00:31:28,285 --> 00:31:29,787
Many folks know them
for making robots

707
00:31:29,820 --> 00:31:32,423
like BigDog and Atlas, WildCat.

708
00:31:33,791 --> 00:31:37,228
They're a very good
company for making robots.

709
00:31:37,261 --> 00:31:39,330
This is a lesser known
robot called RiSe,

710
00:31:39,363 --> 00:31:41,666
and I worked on building
the feet for this robot

711
00:31:41,699 --> 00:31:43,834
with my lab at
Stanford University.

712
00:31:43,867 --> 00:31:46,470
The professor there
is Mark Cutkosky.

713
00:31:46,503 --> 00:31:48,706
It used the first
versions of microspines,

714
00:31:48,739 --> 00:31:52,076
which used gravity just
to engage themselves.

715
00:31:52,109 --> 00:31:54,111
So this robot would only
climb in a straight line,

716
00:31:54,144 --> 00:31:55,813
straight vertically.

717
00:31:57,247 --> 00:31:58,716
Couple of years later, I
took a little bit of break

718
00:31:58,749 --> 00:32:01,652
from my Ph.D. for five or
six weeks and worked for

719
00:32:01,685 --> 00:32:05,189
the Discovery Channel on a
show called Prototype This!

720
00:32:05,222 --> 00:32:06,490
And I'm guessing many
of you didn't see it

721
00:32:06,523 --> 00:32:09,627
'cause it got cancelled
after the first season.

722
00:32:09,660 --> 00:32:12,630
But here, we're showing
paddles, where Lynn,

723
00:32:12,663 --> 00:32:15,533
who's a professional rock
climber, is scaling the outside

724
00:32:15,566 --> 00:32:18,869
of a parking garage
in downtown Oakland.

725
00:32:18,902 --> 00:32:22,974
Each one of those panels
has 1500 microspines,

726
00:32:23,007 --> 00:32:26,477
which is why it took me
six weeks to make them.

727
00:32:26,510 --> 00:32:28,646
And I was very excited,
this was the first time

728
00:32:28,679 --> 00:32:31,315
we had taken them
out and tried them.

729
00:32:31,348 --> 00:32:33,084
So a huge relief.

730
00:32:33,117 --> 00:32:35,052
A younger, skinnier,
very happy version

731
00:32:35,085 --> 00:32:36,454
of me there in the red shirt.

732
00:32:36,487 --> 00:32:39,857
(audience laughing)

733
00:32:39,890 --> 00:32:41,926
So I mentioned these
innovations before.

734
00:32:41,959 --> 00:32:44,729
When I came to JPL, the
question was, how can we use

735
00:32:44,762 --> 00:32:46,564
these climbing
robot technologies

736
00:32:46,597 --> 00:32:48,165
for NASA
applications?

737
00:32:48,198 --> 00:32:51,302
So on Mars, it's not a brick
wall, it's a cliff face, right?

738
00:32:51,335 --> 00:32:52,970
So the same three

things I mentioned.

739
00:32:53,003 --> 00:32:56,407
Conform to the roughness,
opposing microspines

740
00:32:56,440 --> 00:32:58,709
so you can resist
forces in any direction,

741
00:32:58,742 --> 00:33:01,412
and make them out of
space-grade materials.

742
00:33:01,445 --> 00:33:02,913
And so that's what we did.

743
00:33:02,946 --> 00:33:05,016
You can see us testing, pulling
these in different angles

744
00:33:05,049 --> 00:33:08,285
because we've got
that opposed gripper.

745
00:33:08,318 --> 00:33:09,687
Again, notice this
doesn't look like

746
00:33:09,720 --> 00:33:11,288
the ones I've shown you before.

747
00:33:11,321 --> 00:33:13,391
We go through iteration
after iteration.

748
00:33:13,424 --> 00:33:15,059
We make tons of prototypes.

749

00:33:15,092 --> 00:33:18,362
We have a big wall full
of dead prototypes.

750
00:33:18,395 --> 00:33:22,366
That's fun to look at if
you ever get to take a tour.

751
00:33:22,399 --> 00:33:25,736
Here you can see testing,
again, at different angles.

752
00:33:25,769 --> 00:33:28,472
And we test it on all
different kinds of rocks.

753
00:33:28,505 --> 00:33:30,708
And you'll notice the
bottom line there says

754
00:33:30,741 --> 00:33:33,911
limited performance
on granular materials.

755
00:33:33,944 --> 00:33:37,048
These are things like
pebbles, sand, regolith,

756
00:33:37,081 --> 00:33:39,617
powder, that sort of thing.

757
00:33:39,650 --> 00:33:42,887
And I'll tell you a secret,
in an academic paper

758
00:33:42,920 --> 00:33:45,589
or in a talk like this,
if you see something

759
00:33:45,622 --> 00:33:48,692

that says limited
performance, that means zero.

760
00:33:48,725 --> 00:33:50,461
(audience laughing)

761
00:33:50,494 --> 00:33:53,697
This is really a technology
for consolidated rock, right?

762
00:33:53,730 --> 00:33:55,766
If you want to
grip the sand dune

763
00:33:55,799 --> 00:33:59,170
or the regolith field on
the asteroid or the comet,

764
00:33:59,203 --> 00:34:00,971
you need a different
kind of gripper.

765
00:34:01,004 --> 00:34:03,107
You might use the
same kind of robot.

766
00:34:03,140 --> 00:34:05,276
You might use the same autonomy

767
00:34:05,309 --> 00:34:07,745
and the same perception
system, but you're gonna want

768
00:34:07,778 --> 00:34:10,881
a beach umbrella
kind of gripper.

769
00:34:10,914 --> 00:34:12,917
Something that's meant for sand

770
00:34:12,950 --> 00:34:15,787
or these unconsolidated
materials.

771
00:34:18,422 --> 00:34:19,990
So a cool spin-off we got to do.

772
00:34:20,023 --> 00:34:22,793
Because we're able to make
these grippers pretty quickly,

773
00:34:22,826 --> 00:34:25,262
is we made a hand actuated
version of the gripper

774
00:34:25,295 --> 00:34:28,766
that would function
in saltwater.

775
00:34:28,799 --> 00:34:32,403
So this is a neutral buoyancy
test bed that the astronauts

776
00:34:32,436 --> 00:34:35,773
use to practice mocking
up their missions.

777
00:34:35,806 --> 00:34:38,008
Buzz Aldrin, way back
in the Apollo day,

778
00:34:38,041 --> 00:34:40,144
realized that if you wanted
to practice zero gravity

779
00:34:40,177 --> 00:34:43,848
for a long time, one way
is on the Vomit Comet,

780

00:34:43,881 --> 00:34:45,916
but another way
is in a scuba suit

781
00:34:45,949 --> 00:34:48,052
where you can make
yourself neutrally buoyant,

782
00:34:48,085 --> 00:34:49,487
which is actually a
pretty good simulation

783
00:34:49,520 --> 00:34:52,256
for what it's like to
be in zero gravity.

784
00:34:52,289 --> 00:34:54,191
And so here, they're
using microspine grippers

785
00:34:54,224 --> 00:34:56,360
to anchor themselves
to the floor,

786
00:34:56,393 --> 00:34:59,029
which is a simulated
surface of Phobos.

787
00:34:59,062 --> 00:35:01,799
Phobos is one of
the moons of Mars.

788
00:35:01,832 --> 00:35:05,169
And then they're doing other
operations, other samples.

789
00:35:05,202 --> 00:35:07,171
The moons at Mars
are way, way smaller

790

00:35:07,204 --> 00:35:09,106
than the moons of Earth.

791
00:35:09,139 --> 00:35:11,509
So they are actually
microgravity environments

792
00:35:11,542 --> 00:35:13,544
like an asteroid or a comet.

793
00:35:13,577 --> 00:35:15,012
I think there's
actually some debate

794
00:35:15,045 --> 00:35:17,581
about whether those moons
are captured asteroids

795
00:35:17,614 --> 00:35:21,352
or if they're
actually, truly moons.

796
00:35:21,385 --> 00:35:24,021
Here's the rock climbing robot.

797
00:35:24,054 --> 00:35:26,323
This was a video we put
together a couple years ago.

798
00:35:26,356 --> 00:35:29,960
So just like you see different
iterations of the grippers,

799
00:35:29,993 --> 00:35:31,896
we have different
versions of the robot.

800
00:35:31,929 --> 00:35:34,131
So this is LEMUR 2B.

801
00:35:34,164 --> 00:35:36,967
So there's a LEMUR 1, 2,
2A, 2B, we actually have

802
00:35:37,000 --> 00:35:40,804
a LEMUR 3 now, which I'll
show you in just a moment.

803
00:35:40,837 --> 00:35:44,408
I'm gonna skip ahead a
little bit if I can here.

804
00:35:44,441 --> 00:35:45,276
Let's see.

805
00:35:46,343 --> 00:35:48,145
That's the more exciting part.

806
00:35:48,178 --> 00:35:49,880
So this is sped up, as well.

807
00:35:49,913 --> 00:35:52,850
Because when we did
this project,

808
00:35:52,883 --> 00:35:54,718
LEMUR 2B already
existed.

809
00:35:54,751 --> 00:35:55,653
So we said, hey, can
we just use

810
00:35:55,686 --> 00:35:57,154
this robot with our grippers?

811
00:35:57,187 --> 00:35:59,690
Again, try and prototype
and demonstrate something

812
00:35:59,723 --> 00:36:01,759
as fast as we can.

813
00:36:01,792 --> 00:36:04,962
And Brett Kennedy, who had
designed and built this robot,

814
00:36:04,995 --> 00:36:08,098
said sure, but I designed
it to have a peg for a leg,

815
00:36:08,131 --> 00:36:11,168
which only weighs 100 grams.

816
00:36:11,201 --> 00:36:14,138
And I came along and put a one
kilogram gripper on the end,

817
00:36:14,171 --> 00:36:17,808
so it's at the maximum amount
of torque that the motors

818
00:36:17,841 --> 00:36:22,013
can put out in order to
do these kinds of motions.

819
00:36:25,349 --> 00:36:27,518
So all of the videos
are sped up quite a bit.

820
00:36:27,551 --> 00:36:30,921
But as you might know,
going fast, for JPL,

821
00:36:30,954 --> 00:36:33,090
is not necessarily a priority.

822
00:36:33,123 --> 00:36:35,926

It's safety and reliability
that are more important.

823
00:36:35,959 --> 00:36:38,162
So Curiosity on
the surface of Mars

824
00:36:38,195 --> 00:36:41,365
at most goes about
100 meters in a day.

825
00:36:41,398 --> 00:36:42,866
So if you had a
rock climbing robot

826
00:36:42,899 --> 00:36:45,769
that might be able to go two
or three meters in a day,

827
00:36:45,802 --> 00:36:47,771
over the course of a year or
two years, you're actually

828
00:36:47,804 --> 00:36:51,676
gonna cover that cliff
face from top to bottom.

829
00:36:52,943 --> 00:36:55,045
So here's LEMUR 3.

830
00:36:55,078 --> 00:36:57,615
You can see it's got
a lot more joints.

831
00:36:57,648 --> 00:37:01,352
With more joints, it's able
to do more complex motions.

832
00:37:01,385 --> 00:37:05,322
So LEMUR 2 only had three

degrees of freedom per limb,

833
00:37:05,355 --> 00:37:09,527
which meant three motors that
could turn in any given axis.

834
00:37:10,861 --> 00:37:12,930
LEMUR 3 has seven degrees
of freedom per limb,

835
00:37:12,963 --> 00:37:15,232
which is similar to what
you have in a human arm.

836
00:37:15,265 --> 00:37:19,203
So it can put its foot any place
in space at any orientation

837
00:37:19,236 --> 00:37:22,439
plus have one extra degree
of freedom to enable it

838
00:37:22,472 --> 00:37:25,843
to move its body around or
do other sorts of things.

839
00:37:25,876 --> 00:37:27,878
Now this is not a
test wall in our lab.

840
00:37:27,911 --> 00:37:29,113
One of my favorite
parts of the job

841
00:37:29,146 --> 00:37:31,448
is that we get to go
camping with the robots.

842
00:37:31,481 --> 00:37:33,317
And we go out and

we do field tests.

843
00:37:33,350 --> 00:37:35,853
So this is at a pretty
spectacular cave

844
00:37:35,886 --> 00:37:38,722
called El Malpais in New Mexico.

845
00:37:38,755 --> 00:37:40,291
El Malpais is the
national monument,

846
00:37:40,324 --> 00:37:43,360
the cave itself is
called Big Skylight Cave.

847
00:37:43,393 --> 00:37:45,596
You can guess why.

848
00:37:45,629 --> 00:37:47,998
So we climb down in here
and we have the robot

849
00:37:48,031 --> 00:37:51,869
practicing on the side
of this lava tube.

850
00:37:51,902 --> 00:37:53,771
Lave tubes are
really interesting

851
00:37:53,804 --> 00:37:56,206
because we see them on Mars.

852
00:37:56,239 --> 00:37:58,809
So you can see our field
site that we practice on

853

00:37:58,842 --> 00:38:01,478
in New Mexico on the right,
and you can see a picture

854
00:38:01,511 --> 00:38:04,748
that was taken from an
orbiter at Mars on the left.

855
00:38:04,781 --> 00:38:07,451
And the similarities
are really remarkable.

856
00:38:07,484 --> 00:38:10,154
What you'll notice is the
difference is that our

857
00:38:10,187 --> 00:38:12,156
lava tubes on
Earth are smaller,

858
00:38:12,189 --> 00:38:14,425
so 20 meters
versus 50 meters.

859
00:38:14,458 --> 00:38:17,628
Turns out the size of the lava
tubes seems to correlate to

860
00:38:17,661 --> 00:38:21,832
the amount of gravity that
exists on that planet or body.

861
00:38:22,999 --> 00:38:25,869
So on Earth, we see
20, 30 meter max.

862
00:38:25,902 --> 00:38:29,039
On Mars, we see 50,
some even at 100 meters.

863

00:38:29,072 --> 00:38:32,576
On the Moon, we can see them
up to 200 meters in diameter.

864
00:38:32,609 --> 00:38:36,480
So you can imagine
that is a giant cave.

865
00:38:36,513 --> 00:38:37,881
Now caves are really interesting

866
00:38:37,914 --> 00:38:40,584
because they're
preservation environments.

867
00:38:40,617 --> 00:38:42,386
So if you get into a cave,

868
00:38:42,419 --> 00:38:44,355
the environment is
relatively stable.

869
00:38:44,388 --> 00:38:46,590
It never gets too hot,
never gets too cold.

870
00:38:46,623 --> 00:38:48,559
On Mars and the Moon,
you're protected

871
00:38:48,592 --> 00:38:50,894
from radiation as well.

872
00:38:50,927 --> 00:38:54,031
So samples that may be
susceptible to that radiation

873
00:38:54,064 --> 00:38:56,133
haven't volatilized and escaped.

874
00:38:56,166 --> 00:38:59,169
You may have things
that are preserved.

875
00:38:59,202 --> 00:39:02,039
It's no accident that
we find cave paintings

876
00:39:02,072 --> 00:39:04,575
from early man in caves.

877
00:39:04,608 --> 00:39:07,578
It wasn't that they didn't
like painting out in the light,

878
00:39:07,611 --> 00:39:10,180
it was that all of the
paintings on the cliff walls

879
00:39:10,213 --> 00:39:13,250
got washed away and
weathered away over time.

880
00:39:13,283 --> 00:39:17,254
So the only ones we find
now are in the caves.

881
00:39:17,287 --> 00:39:18,956
Here's another picture
of caves on Mars.

882
00:39:18,989 --> 00:39:21,225
We actually have thousands
of these skylights

883
00:39:21,258 --> 00:39:22,893
that we've observed.

884
00:39:22,926 --> 00:39:27,064

And you can see here, several
of them along a sinuous rille.

885
00:39:27,097 --> 00:39:29,233
It sure looks to me
like that's a cave

886
00:39:29,266 --> 00:39:31,668
that's probably
connected underground.

887
00:39:31,701 --> 00:39:33,170
And you can see
from the scale bar,

888
00:39:33,203 --> 00:39:36,340
it's several miles in length.

889
00:39:36,373 --> 00:39:37,808
The other thing that's
good about having

890
00:39:37,841 --> 00:39:40,210
a preservation environment
is if you're a person,

891
00:39:40,243 --> 00:39:42,980
you're not getting
cancer, being blasted

892
00:39:43,013 --> 00:39:45,149
by that radiation
on the surface.

893
00:39:45,182 --> 00:39:49,453
So it may be that we
evolved from cave people

894
00:39:49,486 --> 00:39:51,522
and we will return

to being cave people

895
00:39:51,555 --> 00:39:53,590
when we visit Mars and the Moon

896
00:39:53,623 --> 00:39:58,128
to protect ourselves from
that radiation when we sleep.

897
00:39:58,161 --> 00:40:00,397
Now caves are amazing,
but you might also

898
00:40:00,430 --> 00:40:04,168
want to visit those cliff
faces, as I mentioned before.

899
00:40:04,201 --> 00:40:06,303
And there's plenty
of them on Mars.

900
00:40:06,336 --> 00:40:10,207
The Grand Canyon equivalent
on Mars, Valles Marineris,

901
00:40:10,240 --> 00:40:13,877
is actually much, much
larger than our Grand Canyon.

902
00:40:13,910 --> 00:40:15,913
So you can imagine a
pretty epic mission

903
00:40:15,946 --> 00:40:20,117
having a robot climb from top
to bottom or bottom to top.

904
00:40:22,686 --> 00:40:24,455
And just to emphasize the point,

905
00:40:24,488 --> 00:40:26,156
I don't know how many people
have seen these photos,

906
00:40:26,189 --> 00:40:27,958
they were published by Curiosity

907
00:40:27,991 --> 00:40:32,262
and the Mars science laboratory
team just a few weeks ago,

908
00:40:32,295 --> 00:40:35,332
but these are Murray
Buttes in Gale Crater,

909
00:40:35,365 --> 00:40:38,235
and they really show some
spectacular cliff faces,

910
00:40:38,268 --> 00:40:41,972
and I would love to have
that be our next test site.

911
00:40:42,005 --> 00:40:44,775
And just to emphasize the
cameras that they have now

912
00:40:44,808 --> 00:40:46,810
on these missions
are incredible.

913
00:40:46,843 --> 00:40:50,013
The detail we see, the
layering that you see,

914
00:40:50,046 --> 00:40:54,651
there's so much to explore
beyond what's on the floor.

915

00:40:54,684 --> 00:40:56,353
So rock climbing robots are good

916
00:40:56,386 --> 00:40:57,788
for cliff faces and for caves.

917
00:40:57,821 --> 00:41:00,691
They may also be good
for microgravity.

918
00:41:00,724 --> 00:41:02,092
So moving in
microgravity is more of

919
00:41:02,125 --> 00:41:04,862
a climbing problem
than a walking problem.

920
00:41:04,895 --> 00:41:09,666
If you let go in microgravity,
you fall off, right?

921
00:41:09,699 --> 00:41:12,002
So Itokawa, which
is the asteroid

922
00:41:12,035 --> 00:41:13,704
that the Japanese
visited,

923
00:41:13,737 --> 00:41:18,609
it's about 500 meters across,
the long part of that potato,

924
00:41:18,642 --> 00:41:22,813
and it has the equivalent of
.0003% of Earth's gravity.

925
00:41:25,282 --> 00:41:28,151
And that's pointing sort of

in weird directions, as well,

926
00:41:28,184 --> 00:41:31,154
because that's not a
perfectly spherical body.

927
00:41:31,187 --> 00:41:34,892
So if you jumped off the
surface of Itokawa, no doubt,

928
00:41:34,925 --> 00:41:38,061
you end up in outer
space, never to come back.

929
00:41:38,094 --> 00:41:39,830
If you drop a baseball
on the surface,

930
00:41:39,863 --> 00:41:43,700
takes many minutes for it to
fall down and hit the ground.

931
00:41:43,733 --> 00:41:47,838
So keeping yourself anchored
to the surface is a good idea.

932
00:41:47,871 --> 00:41:50,841
Now these bodies are littered
with boulders and other kinds

933
00:41:50,874 --> 00:41:53,744
of terrain that we might
want to crawl around on.

934
00:41:53,777 --> 00:41:55,012
As I mentioned, the microspines

935
00:41:55,045 --> 00:41:57,147
are good for consolidated rock.

936
00:41:57,180 --> 00:41:59,483
We might have that auger
or that beach umbrella

937
00:41:59,516 --> 00:42:02,152
for the weaker,
granular materials.

938
00:42:02,185 --> 00:42:05,255
The picture on the right was
taken by the Rosetta mission.

939
00:42:05,288 --> 00:42:08,659
That's comet 67P,
I always say CG.

940
00:42:08,692 --> 00:42:11,295
That name is tremendously long.

941
00:42:11,328 --> 00:42:13,263
And these are
incredible pictures,

942
00:42:13,296 --> 00:42:16,567
but wouldn't you like to
have a rover on that body

943
00:42:16,600 --> 00:42:19,202
the same way we have
a rover on Mars?

944
00:42:19,235 --> 00:42:22,039
If you did, you might
start at one lobe

945
00:42:22,072 --> 00:42:25,475
and traverse across the neck
and onto the other lobe.

946

00:42:25,508 --> 00:42:28,078
There's a hypothesis
that 67P might have been

947
00:42:28,111 --> 00:42:31,148
two comets that
got fused together.

948
00:42:31,181 --> 00:42:33,617
We don't have a great way of
testing that because there's

949
00:42:33,650 --> 00:42:36,820
redistribution of the granular
materials on the surface.

950
00:42:36,853 --> 00:42:38,889
So if that fusion happened,

951
00:42:38,922 --> 00:42:41,158
it's kind of been
obscured by now.

952
00:42:41,191 --> 00:42:43,794
But if we could drill, if we
could get under the surface,

953
00:42:43,827 --> 00:42:45,329
we could learn all
kinds of secrets

954
00:42:45,362 --> 00:42:48,098
about the history of that comet.

955
00:42:48,131 --> 00:42:50,901
So you can see places
I've marked with red X's

956
00:42:50,934 --> 00:42:54,171
as example locations in

different geographical units

957
00:42:54,204 --> 00:42:57,040
that we might try and drill.

958
00:42:57,073 --> 00:42:59,576
Here's just a closer in picture,

959
00:42:59,609 --> 00:43:02,680
example pathways
that we might take.

960
00:43:04,114 --> 00:43:06,817
And I'll wrap up with our
beautiful artist concept

961
00:43:06,850 --> 00:43:09,286
of what a rover mission on
the surface of an asteroid

962
00:43:09,319 --> 00:43:11,054
or comet would look like.

963
00:43:11,087 --> 00:43:13,023
I was told, though,
actually if the Earth

964
00:43:13,056 --> 00:43:15,726
is this big in the picture,
it's a bad day for the Earth.

965
00:43:15,759 --> 00:43:17,160
(audience laughing)

966
00:43:17,193 --> 00:43:19,930
We might need that asteroid
deflection technology.

967
00:43:19,963 --> 00:43:23,333

But it makes for a good picture.

968
00:43:23,366 --> 00:43:26,670
Okay, so chapter three
is gecko-like adhesives.

969
00:43:26,703 --> 00:43:28,605
Now gecko adhesives
are very different

970
00:43:28,638 --> 00:43:31,274
than the claw-based approaches
I've been talking about.

971
00:43:31,307 --> 00:43:34,645
You'll sometimes hear me refer
to them as ON-OFF adhesives

972
00:43:34,678 --> 00:43:37,447
because one of the most
remarkable properties

973
00:43:37,480 --> 00:43:40,384
is a gecko can turn the
stickiness of its foot

974
00:43:40,417 --> 00:43:43,320
on and off depending on
which way its pulling on it.

975
00:43:43,353 --> 00:43:45,188
So imagine having duct
tape that you could switch

976
00:43:45,221 --> 00:43:48,425
whether it's sticky
or not sticky.

977
00:43:48,458 --> 00:43:52,429
So geckos, amazing, nature's

best climber by far.

978
00:43:52,462 --> 00:43:54,831
That adhesive is reusable.

979
00:43:54,864 --> 00:43:56,800
We've actually tested
it with some colleagues.

980
00:43:56,833 --> 00:44:00,470
30,000 cycles and the gecko
adhesive didn't wear out.

981
00:44:00,503 --> 00:44:01,672
Can you imagine
if you're a gecko

982
00:44:01,705 --> 00:44:04,274
and your foot stops
sticking after 10 steps,

983
00:44:04,307 --> 00:44:06,410
you're quickly a dead
gecko, which is bad.

984
00:44:06,443 --> 00:44:07,678
(audience laughing)

985
00:44:07,711 --> 00:44:09,513
That ON-OFF behavior,
and the physics

986
00:44:09,546 --> 00:44:12,049
behind this is van
der Waals forces.

987
00:44:12,082 --> 00:44:14,251
And if you remember your
high school physics,

988
00:44:14,284 --> 00:44:17,387
van der Waals forces are
the temporary and weak

989
00:44:17,420 --> 00:44:21,858
interactions that you get
between two electron clouds.

990
00:44:21,891 --> 00:44:24,227
So you bring neutral
atoms very close together,

991
00:44:24,260 --> 00:44:26,396
those electrons are flying
around all over the place,

992
00:44:26,429 --> 00:44:27,964
they don't stay in one spot.

993
00:44:27,997 --> 00:44:30,434
So at any given minute, if
you slice the atom in half,

994
00:44:30,467 --> 00:44:33,537
a few more electrons may be
on one side than on the other.

995
00:44:33,570 --> 00:44:35,672
And if those atoms are
really close together,

996
00:44:35,705 --> 00:44:38,375
they're gonna induce
a matching polarity

997
00:44:38,408 --> 00:44:40,477
in the electron clouds
that are close by.

998

00:44:40,510 --> 00:44:42,279
So you get this net
attractive force

999
00:44:42,312 --> 00:44:44,548
called van der Waals forces.

1000
00:44:44,581 --> 00:44:47,384
Way weaker than
electromagnetic forces,

1001
00:44:47,417 --> 00:44:50,320
way weaker than if the
atom is missing an electron

1002
00:44:50,353 --> 00:44:51,822
and the other one
has an extra electron

1003
00:44:51,855 --> 00:44:54,624
and you've got a covalent
bond or something like that.

1004
00:44:54,657 --> 00:44:56,626
But the gecko can
use those forces

1005
00:44:56,659 --> 00:45:00,063
because of all the tiny
hairs it has on its feet.

1006
00:45:00,096 --> 00:45:03,100
Now some great videos
of geckos here.

1007
00:45:03,133 --> 00:45:06,203
One toe supporting its
entire body weight.

1008
00:45:06,236 --> 00:45:09,706

So it's really sticky, and
that's on glass, by the way.

1009
00:45:09,739 --> 00:45:11,374
And if you look on the
video on the right,

1010
00:45:11,407 --> 00:45:15,812
you can see some really
rich biology going on

1011
00:45:15,845 --> 00:45:18,014
with the curving spine
and the trot gait

1012
00:45:18,047 --> 00:45:20,117
and its curling its toes.

1013
00:45:21,518 --> 00:45:23,053
Geckos could go from the
floor to the ceiling in here

1014
00:45:23,086 --> 00:45:24,888
in about two seconds.

1015
00:45:24,921 --> 00:45:27,958
They take ten steps per second.

1016
00:45:27,991 --> 00:45:30,327
Now imagine trying
to peel duct tape

1017
00:45:30,360 --> 00:45:34,131
and put it back on the surface
ten times in one second.

1018
00:45:34,164 --> 00:45:35,265
You can't because you can't turn

1019

00:45:35,298 --> 00:45:37,167
the stickiness of duct tape off.

1020
00:45:37,200 --> 00:45:39,936
But because the gecko, when
it pulls down on the adhesive,

1021
00:45:39,969 --> 00:45:42,372
is sticky, and when it
releases that weight,

1022
00:45:42,405 --> 00:45:45,476
is un-sticky, it
can fly up the wall.

1023
00:45:47,143 --> 00:45:48,812
So to really
appreciate the gecko,

1024
00:45:48,845 --> 00:45:50,580
you have to have a microscope.

1025
00:45:50,613 --> 00:45:55,485
So geckos have this hierarchical
structure of tiny hairs.

1026
00:45:55,518 --> 00:45:57,220
The only ones you
can see with your eye

1027
00:45:57,253 --> 00:45:59,556
are up here in the upper left.

1028
00:45:59,589 --> 00:46:01,691
They're called lamellae,
and they're flaps.

1029
00:46:01,724 --> 00:46:03,260
They look like flaps, they're on

1030
00:46:03,293 --> 00:46:06,196
the sort of milometer scale.

1031
00:46:06,229 --> 00:46:09,599
Growing on each of those
flaps is a forest of hairs,

1032
00:46:09,632 --> 00:46:11,935
tiny hairs called
setae that are about

1033
00:46:11,968 --> 00:46:16,106
five microns in diameter maybe
a hundred microns in length.

1034
00:46:16,139 --> 00:46:17,474
For reference, a human hair

1035
00:46:17,507 --> 00:46:20,177
is about a hundred
microns in diameter.

1036
00:46:20,210 --> 00:46:22,078
So these hairs are
20 times smaller

1037
00:46:22,111 --> 00:46:23,914
than the hair on your head.

1038
00:46:23,947 --> 00:46:27,017
They grow at an angle, as
well, which is important.

1039
00:46:27,050 --> 00:46:29,486
At the ends of those
hairs, though, down here,

1040
00:46:29,519 --> 00:46:32,222
you see it kind of tufts

like a head of broccoli.

1041
00:46:32,255 --> 00:46:33,990
And that's because
you have branches.

1042
00:46:34,023 --> 00:46:37,394
Each one of those hairs tufts
into dozens if not hundreds

1043
00:46:37,427 --> 00:46:40,730
of branches that are at
the single micron scale.

1044
00:46:40,763 --> 00:46:42,032
Really, really small.

1045
00:46:42,065 --> 00:46:44,501
And those branches
terminate in spatulae,

1046
00:46:44,534 --> 00:46:46,937
which are only tens
of nanometers thick

1047
00:46:46,970 --> 00:46:49,372
and 100, 200 nanometers across.

1048
00:46:49,405 --> 00:46:50,774
And they kind of
look like a spatula,

1049
00:46:50,807 --> 00:46:53,510
although that's a
coincidence with the name.

1050
00:46:53,543 --> 00:46:55,612
Those are what makes
contact with the surface

1051
00:46:55,645 --> 00:46:58,648
and what uses those van
der Waals forces to stick.

1052
00:46:58,681 --> 00:47:00,684
So the genius of
the gecko system

1053
00:47:00,717 --> 00:47:03,653
is that it has this intricate
suspension structure

1054
00:47:03,686 --> 00:47:07,190
behind those spatulae that
help it conform to the surface

1055
00:47:07,223 --> 00:47:12,028
and load share without pushing
the animal back off the wall.

1056
00:47:12,061 --> 00:47:15,398
I can jam my hand into a
surface and generate some

1057
00:47:15,431 --> 00:47:18,168
van der Waals forces, but
because the deflection

1058
00:47:18,201 --> 00:47:22,138
of the tissue in my hand
is greater in terms of

1059
00:47:22,171 --> 00:47:24,641
a spring back force
than the adhesion I get

1060
00:47:24,674 --> 00:47:27,577
from the van der Waals forces,
I can't climb up the wall.

1061
00:47:27,610 --> 00:47:30,080
Unfortunately, that
would be great.

1062
00:47:30,113 --> 00:47:31,648
But a gecko can do it.

1063
00:47:31,681 --> 00:47:35,252
Now manufacturing
something that intricate

1064
00:47:35,285 --> 00:47:37,754
is still probably 50 years out.

1065
00:47:37,787 --> 00:47:39,222
We just don't have
the technology

1066
00:47:39,255 --> 00:47:42,459
to make something like
the gecko is able to grow.

1067
00:47:42,492 --> 00:47:45,328
We can make thing at the
nanoscale like nanotubes.

1068
00:47:45,361 --> 00:47:47,163
We can make things at
the milometer scale.

1069
00:47:47,196 --> 00:47:51,568
But making them together, and
non-coplanar and branching,

1070
00:47:51,601 --> 00:47:53,637
it's just too much.

1071
00:47:53,670 --> 00:47:55,939
So as an engineer, I

don't wanna wait 50 years

1072
00:47:55,972 --> 00:47:57,874
for the technology
to come around.

1073
00:47:57,907 --> 00:47:59,676
So we do biomimetics.

1074
00:48:00,843 --> 00:48:02,045
We're not trying
to copy the gecko,

1075
00:48:02,078 --> 00:48:03,747
we're trying to
learn the lessons

1076
00:48:03,780 --> 00:48:06,149
and apply them in our robots.

1077
00:48:06,182 --> 00:48:08,351
So one of the lessons
is this directionality.

1078
00:48:08,384 --> 00:48:10,787
You can see this
hair has an angle.

1079
00:48:10,820 --> 00:48:13,490
These hairs are about 20
microns across the base.

1080
00:48:13,523 --> 00:48:15,125
So they are about
five times smaller

1081
00:48:15,158 --> 00:48:16,993
than the hair on your head.

1082

00:48:17,026 --> 00:48:19,062
And they're made out
of a silicone rubber.

1083
00:48:19,095 --> 00:48:21,164
So gecko hairs are actually
made out of beta-carotene,

1084
00:48:21,197 --> 00:48:23,767
which is like a
fingernail or lizard skin.

1085
00:48:23,800 --> 00:48:25,001
It's rough.

1086
00:48:25,034 --> 00:48:27,170
We cheat by using a
rubbery-like material.

1087
00:48:27,203 --> 00:48:29,606
Not a sticky material, but
something a little softer

1088
00:48:29,639 --> 00:48:32,442
that lets us get a
little bit more adhesion.

1089
00:48:32,475 --> 00:48:35,745
Just because we can't
match that geometry.

1090
00:48:35,778 --> 00:48:37,347
You can see that same property

1091
00:48:37,380 --> 00:48:40,850
if you pull the gecko
hairs along the surface,

1092
00:48:40,883 --> 00:48:43,753
they bend over, you get a

high, real area of contact,

1093
00:48:43,786 --> 00:48:46,790
lots of van der Waals
forces, and they stick.

1094
00:48:46,823 --> 00:48:48,925
If you push them in
the opposite direction

1095
00:48:48,958 --> 00:48:51,861
or you don't load them at
all, it's only the very tips

1096
00:48:51,894 --> 00:48:54,130
of these hairs, it's only
this point, right here,

1097
00:48:54,163 --> 00:48:56,366
that makes contact with the
surface, and you don't have

1098
00:48:56,399 --> 00:48:59,436
any van der Waals
forces, it doesn't stick.

1099
00:48:59,469 --> 00:49:01,838
We add a tip to these features,

1100
00:49:01,871 --> 00:49:04,007
we've been collaborating
with Elliot Hawkes

1101
00:49:04,040 --> 00:49:07,010
and my old advisor Mark
Cutcosky at Stanford,

1102
00:49:07,043 --> 00:49:08,912
we've really never
stopped working together

1103
00:49:08,945 --> 00:49:11,114
since I was a young
master's student,

1104
00:49:11,147 --> 00:49:13,850
to add this mushroom shaped tip,

1105
00:49:13,883 --> 00:49:16,186
and that gives you
about twice the adhesion

1106
00:49:16,219 --> 00:49:20,123
'cause you have a thin
film effect at the edges.

1107
00:49:20,156 --> 00:49:22,525
So the way we make these,

1108
00:49:22,558 --> 00:49:24,194
I'll try and do it very quickly,

1109
00:49:24,227 --> 00:49:26,663
I'm gonna speak MEMS
technology here for a minute.

1110
00:49:26,696 --> 00:49:28,999
So if you don't
understand, don't worry.

1111
00:49:29,032 --> 00:49:33,036
We use a quartz wafer, and
then we hard mask that in metal

1112
00:49:33,069 --> 00:49:36,840
so that we can do an
exposure through that wafer.

1113
00:49:36,873 --> 00:49:39,909

Quartz is transparent to
UV light so we can have

1114
00:49:39,942 --> 00:49:43,313
UV light come through this
wafer from the back side

1115
00:49:43,346 --> 00:49:46,549
and expose where we
haven't blocked it off.

1116
00:49:46,582 --> 00:49:48,651
We then align and do
a vertical exposure

1117
00:49:48,684 --> 00:49:52,322
and then develop, and what
you end up with is a mold.

1118
00:49:52,355 --> 00:49:55,158
So we have a negative
version of that shape

1119
00:49:55,191 --> 00:49:57,560
that we can cast into
over and over again.

1120
00:49:57,593 --> 00:49:58,862
So we use that silicone rubber,

1121
00:49:58,895 --> 00:50:00,930
which starts kind of
like 5 Minute Epoxy.

1122
00:50:00,963 --> 00:50:03,400
It's two parts of liquid,
you mix it together,

1123
00:50:03,433 --> 00:50:06,536
you pour it in, and

voila, it solidifies,

1124
00:50:06,569 --> 00:50:07,804
and you can peel it out.

1125
00:50:07,837 --> 00:50:10,507
You do that over and over again.

1126
00:50:12,341 --> 00:50:14,310
To understand the
behavior, we test that

1127
00:50:14,343 --> 00:50:16,046
at all different angles.

1128
00:50:16,079 --> 00:50:19,182
So we pull on that gecko
material with sheer

1129
00:50:19,215 --> 00:50:21,184
or with no sheer, and
the key point here,

1130
00:50:21,217 --> 00:50:22,886
is this goes through the origin.

1131
00:50:22,919 --> 00:50:25,655
Which means if you don't
pull across the surface,

1132
00:50:25,688 --> 00:50:27,190
it doesn't stick.

1133
00:50:27,223 --> 00:50:29,292
And if you release that
force across the surface,

1134
00:50:29,325 --> 00:50:30,794
it comes off.

1135
00:50:30,827 --> 00:50:33,830
You can see with the more force
along the surface you have,

1136
00:50:33,863 --> 00:50:35,698
the more stickiness you have.

1137
00:50:35,731 --> 00:50:37,534
This axis is your stickiness,

1138
00:50:37,567 --> 00:50:41,004
and this axis is your
pulling along the surface.

1139
00:50:41,037 --> 00:50:43,139
And that maxes
out at some point,

1140
00:50:43,172 --> 00:50:45,742
and then you kind of asymptote.

1141
00:50:46,943 --> 00:50:48,344
So I'll get back to a
more interesting thing,

1142
00:50:48,377 --> 00:50:50,847
here's the first robots
that we were testing

1143
00:50:50,880 --> 00:50:52,782
with this gecko-like adhesive.

1144
00:50:52,815 --> 00:50:54,250
We called it Stickybot.

1145
00:50:54,283 --> 00:50:56,719
In fact, this is Stickybot
2, so I was learning

1146
00:50:56,752 --> 00:51:00,290
iterative design even
when I was in school.

1147
00:51:00,323 --> 00:51:01,624
You can see, it's
very gecko-like

1148
00:51:01,657 --> 00:51:03,626
in more ways than just the feet.

1149
00:51:03,659 --> 00:51:06,663
Sangbae Kim was the main
guy who designed the robot.

1150
00:51:06,696 --> 00:51:08,898
I really worked on the
feet for this robot.

1151
00:51:08,931 --> 00:51:10,834
He's now a professor at
MIT, you may have seen

1152
00:51:10,867 --> 00:51:15,805
his Cheetah robots if you've
seen any of the YouTube videos.

1153
00:51:15,838 --> 00:51:17,841
I like to joke, people
in Thailand come down

1154
00:51:17,874 --> 00:51:20,777
and they see a gecko running
up their kitchen cupboard.

1155
00:51:20,810 --> 00:51:22,745
In our lab at Stanford,
we would come down

1156
00:51:22,778 --> 00:51:27,417
and we would see a robot
gecko running up the cupboard.

1157
00:51:27,450 --> 00:51:31,788
This gecko used gravity to
engage that ON-OFF behavior.

1158
00:51:31,821 --> 00:51:33,556
So again, it only
climbed in a vertical

1159
00:51:33,589 --> 00:51:36,093
straight line against gravity.

1160
00:51:37,226 --> 00:51:39,162
We have to do a
trick if we're gonna

1161
00:51:39,195 --> 00:51:42,298
get it to work in zero
gravity, in space.

1162
00:51:42,331 --> 00:51:44,467
And it's the same trick
a gecko does, actually.

1163
00:51:44,500 --> 00:51:47,103
You can see here, if a
gecko's sideways on a wall,

1164
00:51:47,136 --> 00:51:49,639
it orients its feet so
that gravity is pointing

1165
00:51:49,672 --> 00:51:52,709
in the preferred direction
to make their feet sticky.

1166

00:51:52,742 --> 00:51:56,312
And if they flip upside down
to go head first down the wall

1167
00:51:56,345 --> 00:51:57,981
they actually rotate their feet,

1168
00:51:58,014 --> 00:52:00,216
again so that they're in
the preferred direction

1169
00:52:00,249 --> 00:52:02,652
so gravity turns
the stickiness on.

1170
00:52:02,685 --> 00:52:04,120
The first person
to observe this,

1171
00:52:04,153 --> 00:52:06,122
or at least the first
person to write it down,

1172
00:52:06,155 --> 00:52:08,658
was actually Aristotle
in one of his books.

1173
00:52:08,691 --> 00:52:11,594
So kind of cool side note
is I got to cite Aristotle

1174
00:52:11,627 --> 00:52:13,730
in my Ph.D. thesis,
(audience laughing)

1175
00:52:13,763 --> 00:52:16,299
which I thought was great.

1176
00:52:16,332 --> 00:52:17,967
Now so we use that

trick to our advantage

1177
00:52:18,000 --> 00:52:20,036
in the same way we do
with the microspines.

1178
00:52:20,069 --> 00:52:23,339
Put two gecko pads in
opposition, squeeze together,

1179
00:52:23,372 --> 00:52:25,074
and you're gonna get
an adhesive anchor

1180
00:52:25,107 --> 00:52:27,777
that can support loads
in any direction.

1181
00:52:27,810 --> 00:52:28,978
You can do it with two pads,

1182
00:52:29,011 --> 00:52:31,948
you can do it with
a lot of pads.

1183
00:52:31,981 --> 00:52:34,317
Of course, since it's
supposed to work in zero G,

1184
00:52:34,350 --> 00:52:37,487
we gotta take it on the
airplane, test it out.

1185
00:52:37,520 --> 00:52:40,823
So here's me grappling
a free-floating cube

1186
00:52:40,856 --> 00:52:43,960
during one of those
zero G moments.

1187
00:52:43,993 --> 00:52:46,229
So this is a video, again,
collaborating with Stanford

1188
00:52:46,262 --> 00:52:50,233
to demonstrate some of the
properties of these grippers.

1189
00:52:50,266 --> 00:52:51,467
One of the key things is

1190
00:52:51,500 --> 00:52:53,369
you don't have to push
it into the surface.

1191
00:52:53,402 --> 00:52:55,505
You just have to pull
along the surface.

1192
00:52:55,538 --> 00:52:57,540
So unlike duct tape, again,
where you have to sort of

1193
00:52:57,573 --> 00:53:00,810
make sure it's pressed down
firmly to get it to stick well,

1194
00:53:00,843 --> 00:53:03,880
with a gecko-like adhesive you
just touch it to the surface,

1195
00:53:03,913 --> 00:53:05,315
and it sticks.

1196
00:53:05,348 --> 00:53:07,717
And similarly, you can
release it with zero force.

1197

00:53:07,750 --> 00:53:12,021
It doesn't fall or push that
plate away when he lets go.

1198
00:53:12,054 --> 00:53:14,857
We've done testing here at JPL
in a thermal vacuum chamber

1199
00:53:14,890 --> 00:53:17,493
so it does work in the
environment you find in space,

1200
00:53:17,526 --> 00:53:20,030
minus 60 Celsius, full vacuum.

1201
00:53:21,197 --> 00:53:22,699
We've done over 30,000 cycles

1202
00:53:22,732 --> 00:53:25,335
with our synthetic
gecko adhesive.

1203
00:53:25,368 --> 00:53:27,503
And here we're demonstrating
one of the use cases,

1204
00:53:27,536 --> 00:53:30,607
where we might try and grapple
a piece of orbital debris,

1205
00:53:30,640 --> 00:53:33,643
a piece of space garbage, and
try and tow it out of the way,

1206
00:53:33,676 --> 00:53:35,979
make sure it doesn't
hit astronauts

1207
00:53:36,012 --> 00:53:37,113
like that

movie Gravity,

1208
00:53:37,146 --> 00:53:40,483
make sure that we can
protect our assets.

1209
00:53:40,516 --> 00:53:43,519
Now we wanted to test a
hundred kilogram cube,

1210
00:53:43,552 --> 00:53:46,623
which is basically a
refrigerator, and we asked NASA,

1211
00:53:46,656 --> 00:53:49,058
can we fly a refrigerator
inside the airplane?

1212
00:53:49,091 --> 00:53:50,760
And they said, heck no.
(audience laughing)

1213
00:53:50,793 --> 00:53:52,595
And so we were bummed
for a couple of days

1214
00:53:52,628 --> 00:53:54,998
until one of our
students, Jonathon there,

1215
00:53:55,031 --> 00:53:57,567
said y'know I'm
about 100 kilograms.

1216
00:53:57,600 --> 00:54:00,203
And so we put a vest
on him, and he became

1217
00:54:00,236 --> 00:54:02,239
the high inertia target.

1218
00:54:03,706 --> 00:54:05,041
And that's one of our
other interns at the time,

1219
00:54:05,074 --> 00:54:08,511
who now works here,
grappling him.

1220
00:54:08,544 --> 00:54:10,480
Another facility we have at JPL

1221
00:54:10,513 --> 00:54:13,516
to test in a zero
G-like environment

1222
00:54:13,549 --> 00:54:16,619
is the Robo-Dome or the
Formation Control Testbed.

1223
00:54:16,652 --> 00:54:18,521
It's like a giant
air hockey table,

1224
00:54:18,554 --> 00:54:21,157
but these robots are pumping
the air out the bottom

1225
00:54:21,190 --> 00:54:23,159
instead of the air
coming through the table.

1226
00:54:23,192 --> 00:54:25,228
The robots weigh
about 800 pounds each,

1227
00:54:25,261 --> 00:54:27,463
but you can push
them with your pinky.

1228
00:54:27,496 --> 00:54:30,199
And in this demonstration,
we used thrusters

1229
00:54:30,232 --> 00:54:33,336
on the gold robot to
chase down the blue one,

1230
00:54:33,369 --> 00:54:35,004
grapple it with
the gecko adhesive,

1231
00:54:35,037 --> 00:54:37,774
and tow it back
to a set position.

1232
00:54:37,807 --> 00:54:40,276
So this is a mission that
you might see in space

1233
00:54:40,309 --> 00:54:42,478
if you're grappling a
satellite that's gone

1234
00:54:42,511 --> 00:54:45,248
out of its preferred orbit
and putting it back in place,

1235
00:54:45,281 --> 00:54:49,286
maybe doing repair,
refueling on that satellite.

1236
00:54:50,720 --> 00:54:52,322
Of course, I'm a roboticist,
and so I wanna see robots

1237
00:54:52,355 --> 00:54:54,490
crawling around on everything.

1238

00:54:54,523 --> 00:54:56,492
Here's an artist
concept of a robot

1239
00:54:56,525 --> 00:54:58,861
inspecting the outside
of the space station.

1240
00:54:58,894 --> 00:55:02,498
And if we send humans to
Mars, that journey to Mars,

1241
00:55:02,531 --> 00:55:05,501
you may find robots to
maintain that space station,

1242
00:55:05,534 --> 00:55:09,272
make sure it's functioning,
do light repairs.

1243
00:55:11,107 --> 00:55:13,509
So we've done some
work on this, as well.

1244
00:55:13,542 --> 00:55:16,946
In this case, we're using
a counterweight to reduce

1245
00:55:16,979 --> 00:55:20,883
the gravity and allow us
to climb around in zero G.

1246
00:55:20,916 --> 00:55:23,419
Now I knew you guys were
gonna be a smart audience,

1247
00:55:23,452 --> 00:55:26,322
and so I sped up the video
that was already sped up

1248

00:55:26,355 --> 00:55:31,094
so any of those numbers
you see, multiply by three.

1249
00:55:31,127 --> 00:55:33,596
So you can see it
gripping and releasing.

1250
00:55:33,629 --> 00:55:36,866
And you can see this is LEMUR
3 just with different feet.

1251
00:55:36,899 --> 00:55:39,335
We use LEMUR 3 for rock
climbing with the microspines.

1252
00:55:39,368 --> 00:55:42,372
Use LEMUR 3 for ISS inspection

1253
00:55:42,405 --> 00:55:45,742
kinds of challenges
with gecko grippers.

1254
00:55:48,978 --> 00:55:50,613
Now earlier this
year my first piece

1255
00:55:50,646 --> 00:55:52,715
of hardware got sent to space.

1256
00:55:52,748 --> 00:55:54,317
This was in May.

1257
00:55:54,350 --> 00:55:56,886
I did not take this picture,
but I was very close to

1258
00:55:56,919 --> 00:55:59,889
this spot, and my picture
looks nothing like this.

1259
00:55:59,922 --> 00:56:01,357
(audience laughing)

1260
00:56:01,390 --> 00:56:03,693
But here's a resupply
mission going to the ISS,

1261
00:56:03,726 --> 00:56:06,696
it was a night launch, it
was awesome to see it go.

1262
00:56:06,729 --> 00:56:08,464
And we put a few gecko grippers

1263
00:56:08,497 --> 00:56:10,266
in the hands of the astronauts.

1264
00:56:10,299 --> 00:56:12,368
So here's Jeff Williams.

1265
00:56:12,401 --> 00:56:15,204
He's attached a gecko
gripper to the bulkhead.

1266
00:56:15,237 --> 00:56:16,572
And then he's gonna
take out a force gauge

1267
00:56:16,605 --> 00:56:19,008
and tug on it and
measure the force.

1268
00:56:19,041 --> 00:56:20,343
We also had them
leave those grippers

1269
00:56:20,376 --> 00:56:22,512
in place for a few weeks,

1270
00:56:22,545 --> 00:56:24,347
just to demonstrate that
it doesn't wear out,

1271
00:56:24,380 --> 00:56:27,049
doesn't need any power
to stay attached.

1272
00:56:27,082 --> 00:56:28,418
And my favorite part right here,

1273
00:56:28,451 --> 00:56:30,052
this is the first
time he does it,

1274
00:56:30,085 --> 00:56:31,821
he thinks it's gonna pull off.

1275
00:56:31,854 --> 00:56:34,357
Then he realizes, oop,
I gotta brace myself,

1276
00:56:34,390 --> 00:56:37,060
because that's a sticky gripper.

1277
00:56:39,528 --> 00:56:41,531
There are opportunities to use

1278
00:56:41,564 --> 00:56:43,800
this technology here on Earth.

1279
00:56:43,833 --> 00:56:45,668
We've partnered with
a startup company

1280
00:56:45,701 --> 00:56:48,671
called Perception
Robotics that's here in LA

1281
00:56:48,704 --> 00:56:51,607
that wants to put gecko
grippers onto the factory floor

1282
00:56:51,640 --> 00:56:54,110
to do pick and place operations,
those kinds of things.

1283
00:56:54,143 --> 00:56:56,612
And they sent me
this picture one day,

1284
00:56:56,645 --> 00:56:58,848
which I was not expecting,
where they were at

1285
00:56:58,881 --> 00:57:01,884
a small business event,
and President Obama

1286
00:57:01,917 --> 00:57:03,953
and Chancellor Merkel stopped by

1287
00:57:03,986 --> 00:57:07,190
and I actually built that
gripper that we had given

1288
00:57:07,223 --> 00:57:10,560
to the company to do testing
and demonstrations with.

1289
00:57:10,593 --> 00:57:14,197
So they sent me this
picture, and I--

1290
00:57:14,230 --> 00:57:15,031
Holy cow.

1291

00:57:15,064 --> 00:57:17,867
(audience laughing)

1292
00:57:17,900 --> 00:57:20,570
So we're onto the fourth
chapter, and we're gonna do

1293
00:57:20,603 --> 00:57:23,840
a rapid fire kind of
whirlwind through some of

1294
00:57:23,873 --> 00:57:27,877
the early stage prototypes
we have in the lab.

1295
00:57:27,910 --> 00:57:30,246
So we've put some of these
adhesive technologies

1296
00:57:30,279 --> 00:57:31,981
onto wheeled robots.

1297
00:57:32,014 --> 00:57:33,916
We're trying to
miniaturize robots.

1298
00:57:33,949 --> 00:57:36,486
Get them as small as possible.

1299
00:57:36,519 --> 00:57:38,120
So you can see here
the microspines

1300
00:57:38,153 --> 00:57:39,789
climbing up rough surfaces.

1301
00:57:39,822 --> 00:57:42,826
(audience laughing)

1302

00:57:44,126 --> 00:57:45,461
And you'll notice
there's no safety line.

1303
00:57:45,494 --> 00:57:47,396
We try and make these
sort of crash proof

1304
00:57:47,429 --> 00:57:50,633
so that they can survive
if they are to fall off

1305
00:57:50,666 --> 00:57:51,801
(audience laughing)

1306
00:57:51,834 --> 00:57:53,169
or if we intentionally
drive them off.

1307
00:57:53,202 --> 00:57:54,770
This was especially
fulfilling 'cause we eat lunch

1308
00:57:54,803 --> 00:57:57,306
right next to these stairs,
so we would look at it

1309
00:57:57,339 --> 00:57:59,308
every day and say,
one day we're gonna

1310
00:57:59,341 --> 00:58:02,078
have the robot climb
up those stairs.

1311
00:58:02,111 --> 00:58:04,814
You see Kalind Carpenter
there controlling the robot.

1312
00:58:04,847 --> 00:58:07,884

He did most of the work
here to make that a reality.

1313
00:58:07,917 --> 00:58:09,385
So it was another fun
day when we were out

1314
00:58:09,418 --> 00:58:11,387
at the tallest brick
building we could find,

1315
00:58:11,420 --> 00:58:12,889
it's about six stories.

1316
00:58:12,922 --> 00:58:14,857
The robot made it all
the way to the top.

1317
00:58:14,890 --> 00:58:17,493
And then we realized that the
latch to the roof was locked.

1318
00:58:17,526 --> 00:58:18,394
(audience laughing)

1319
00:58:18,427 --> 00:58:19,896
And we couldn't get up there.

1320
00:58:19,929 --> 00:58:22,932
So we brought out a fishing
net and tried to catch it.

1321
00:58:22,965 --> 00:58:25,067
And we made it fall
off, and we missed.

1322
00:58:25,100 --> 00:58:28,104
(audience laughing)

1323

00:58:30,906 --> 00:58:34,477
So one story kind of
falls, we can survive.

1324
00:58:34,510 --> 00:58:36,379
That six story was
a little tough.

1325
00:58:36,412 --> 00:58:40,383
But here you can see some
of our impact testing.

1326
00:58:40,416 --> 00:58:42,618
The robot keeps going.

1327
00:58:42,651 --> 00:58:44,520
Now it's the same
robot, but here

1328
00:58:44,553 --> 00:58:46,322
it's got a different
kind of wheel.

1329
00:58:46,355 --> 00:58:47,590
These are the
electrostatic wheels

1330
00:58:47,623 --> 00:58:49,559
that I mentioned at
the very beginning.

1331
00:58:49,592 --> 00:58:53,963
So they operate at a very high
voltage, about 5000 volts,

1332
00:58:53,996 --> 00:58:56,465
but they are only creating
a charge differential.

1333
00:58:56,498 --> 00:58:58,868

So they're not powering
anything, they're just keeping

1334
00:58:58,901 --> 00:59:02,738
the charge between the
pad and the surface.

1335
00:59:02,771 --> 00:59:05,241
The reason the balloon falls
off the wall after a while

1336
00:59:05,274 --> 00:59:06,842
is 'cause that
charge differential

1337
00:59:06,875 --> 00:59:08,077
bleeds off
into the air.

1338
00:59:08,110 --> 00:59:09,579
So you hook up a
circuit to the balloon

1339
00:59:09,612 --> 00:59:11,314
after you rub it on your
head, it'll stay up there

1340
00:59:11,347 --> 00:59:14,183
as long as your
battery has power.

1341
00:59:15,517 --> 00:59:17,353
So the electrostatic
adhesives, we're partnering

1342
00:59:17,386 --> 00:59:20,790
with Matt Spenko at Illinois
Institute of Technology.

1343
00:59:20,823 --> 00:59:24,660

And these are used,
electrodes that are sort of

1344
00:59:24,693 --> 00:59:28,097
interstitial like this, powered
at that very high voltage.

1345
00:59:28,130 --> 00:59:30,499
I put one equation
in the entire talk,

1346
00:59:30,532 --> 00:59:32,835
'cause I felt like you
have to have one equation.

1347
00:59:32,868 --> 00:59:34,036
But it's a really easy one.

1348
00:59:34,069 --> 00:59:35,771
So it says, the force
you get from this

1349
00:59:35,804 --> 00:59:40,142
is a product of the
polarizability of the material,

1350
00:59:40,175 --> 00:59:42,912
how easy it is to create
an electric field in it,

1351
00:59:42,945 --> 00:59:45,948
so metals are really high,
clay and things are really low,

1352
00:59:45,981 --> 00:59:49,552
and the strength of
your electric field.

1353
00:59:49,585 --> 00:59:51,053
Of course, we got a new robot,

1354
00:59:51,086 --> 00:59:53,923
we gotta test it in
the zero G airplane.

1355
00:59:53,956 --> 00:59:56,325
So here we're showing
the first demonstrations

1356
00:59:56,358 --> 00:59:59,095
of zero G mobility,
I think ever.

1357
01:00:00,162 --> 01:00:01,397
I think this is the first robot

1358
01:00:01,430 --> 01:00:04,534
that's ever climbed
around in zero G.

1359
01:00:05,701 --> 01:00:07,169
We have had some free flyers

1360
01:00:07,202 --> 01:00:09,605
that are sort of
hovering and fly around.

1361
01:00:09,638 --> 01:00:11,941
This is the first
crawler that I know of.

1362
01:00:11,974 --> 01:00:14,543
So here's a spare solar panel.

1363
01:00:14,576 --> 01:00:16,345
This was actually an
extra from a satellite

1364
01:00:16,378 --> 01:00:18,047

that went up to GEO.

1365
01:00:18,947 --> 01:00:21,617
The slide before was mylar,

1366
01:00:21,650 --> 01:00:24,053
which is a common
thermal blanket material.

1367
01:00:24,086 --> 01:00:25,521
So the outsides of spacecraft

1368
01:00:25,554 --> 01:00:27,390
are covered in these
kinds of things.

1369
01:00:27,423 --> 01:00:30,726
Here, Christine is grappling
a one meter cylinder.

1370
01:00:30,759 --> 01:00:32,461
We chose one meter and aluminum

1371
01:00:32,494 --> 01:00:35,364
because that's the materials
of the Thor booster.

1372
01:00:35,397 --> 01:00:37,500
So back in the 60s and 70s
we weren't so concerned

1373
01:00:37,533 --> 01:00:40,002
about all the garbage
that we put up in space,

1374
01:00:40,035 --> 01:00:41,704
and there's hundreds of boosters

1375
01:00:41,737 --> 01:00:44,540

that are about that diameter,
so we're demonstrating

1376
01:00:44,573 --> 01:00:46,709
the ability to
grapple one of those.

1377
01:00:46,742 --> 01:00:49,178
It wouldn't be cost effective
to do that with all of them,

1378
01:00:49,211 --> 01:00:51,981
but if one of them's coming to
hit a very high value asset,

1379
01:00:52,014 --> 01:00:54,250
like the International
Space Station,

1380
01:00:54,283 --> 01:00:58,120
it'd be great to protect
yourself from that.

1381
01:00:58,153 --> 01:01:01,590
Here's an inchworm-style version
using gecko-like materials.

1382
01:01:01,623 --> 01:01:03,225
It's a lot slower,
so it was only taking

1383
01:01:03,258 --> 01:01:05,261
one step each parabola.

1384
01:01:06,395 --> 01:01:07,963
And then we're having
some fun at the end,

1385
01:01:07,996 --> 01:01:12,635
testing out the robot on

these curved surfaces.

1386
01:01:12,668 --> 01:01:14,236
So we've also done
some rapid prototyping

1387
01:01:14,269 --> 01:01:16,005
with a volcano bot.

1388
01:01:16,038 --> 01:01:18,374
This is Carolyn Parcheta.

1389
01:01:18,407 --> 01:01:22,745
She is bold, and I'm
terrified when we're here.

1390
01:01:22,778 --> 01:01:24,046
This is in Hawaii.

1391
01:01:24,079 --> 01:01:27,316
She came to our lab
and wanted to image

1392
01:01:28,717 --> 01:01:32,021
underground conduits for
fissure-style eruptions.

1393
01:01:32,054 --> 01:01:33,989
Now Carolyn is a volcanologist.

1394
01:01:34,022 --> 01:01:38,527
She has her doctorate in
Geology and Volcanology,

1395
01:01:38,560 --> 01:01:41,097
but she came to our lab and
asked us to build a robot

1396
01:01:41,130 --> 01:01:44,433

with her to image these
underground vents.

1397
01:01:44,466 --> 01:01:47,436
She had taken lidar and
imaged them from the surface,

1398
01:01:47,469 --> 01:01:50,239
but because the vents have
some sinuosity to them,

1399
01:01:50,272 --> 01:01:51,173
she was only to be able to get

1400
01:01:51,206 --> 01:01:52,842
about two or three meters deep.

1401
01:01:52,875 --> 01:01:55,478
Lidar only works line of sight.

1402
01:01:57,045 --> 01:01:59,215
I love this robot because
it's really a great example

1403
01:01:59,248 --> 01:02:02,618
of the methodology we try
and embrace in the lab.

1404
01:02:02,651 --> 01:02:06,422
We used 3D printers, motors
we already had on the shelf,

1405
01:02:06,455 --> 01:02:09,725
Arduino micro controllers
that we already had code for.

1406
01:02:09,758 --> 01:02:13,562
We basically duct taped a robot
together as fast as we could

1407
01:02:13,595 --> 01:02:16,532
and she and I were out
in the field in Hawaii

1408
01:02:16,565 --> 01:02:19,268
about four months later
testing that robot

1409
01:02:19,301 --> 01:02:22,872
with an Xbox Kinect
as the sensor.

1410
01:02:22,905 --> 01:02:26,308
Off the shelf system to map
that underground conduit.

1411
01:02:26,341 --> 01:02:29,578
And she had spent her Ph.D.
studying these same fissures

1412
01:02:29,611 --> 01:02:31,213
and had gotten that lidar data,

1413
01:02:31,246 --> 01:02:33,716
and even though the
robot on that first trip

1414
01:02:33,749 --> 01:02:37,186
only worked about 20% of the
time, we spent most of our days

1415
01:02:37,219 --> 01:02:40,222
in the hotel room trying to
fix it, we were able to get

1416
01:02:40,255 --> 01:02:42,992
some data that was
first of its kind.

1417

01:02:43,025 --> 01:02:45,394
Where we're imaging the fissure,
we went all the way down

1418
01:02:45,427 --> 01:02:48,164
to 40 meters, and we
ran out of tether.

1419
01:02:48,197 --> 01:02:50,499
So from three meters
to now 40 meters.

1420
01:02:50,532 --> 01:02:53,636
And we iterated on that, and
we went back this past spring,

1421
01:02:53,669 --> 01:02:55,938
and the third of fourth
version of the robot

1422
01:02:55,971 --> 01:02:59,742
basically worked from dusk until
dawn for two straight weeks

1423
01:02:59,775 --> 01:03:03,612
and we have a map now of
the entire conduit system

1424
01:03:03,645 --> 01:03:06,549
of one of these
fissure eruptions.

1425
01:03:07,749 --> 01:03:09,318
So if you look at that
data that you get back

1426
01:03:09,351 --> 01:03:10,953
it's generally point cloud data.

1427
01:03:10,986 --> 01:03:12,621

We're interested in
this for some of our

1428
01:03:12,654 --> 01:03:14,623
rock climbing robots, as well.

1429
01:03:14,656 --> 01:03:17,293
This is the kind of
thing you get back.

1430
01:03:17,326 --> 01:03:19,695
And we're interested in
ways to visualize that data

1431
01:03:19,728 --> 01:03:21,964
besides just showing
it on a computer screen

1432
01:03:21,997 --> 01:03:23,833
so we may try and integrate
it into some of those

1433
01:03:23,866 --> 01:03:26,168
virtual reality goggles
so you could actually have

1434
01:03:26,201 --> 01:03:28,537
a scientist be
inside that fissure

1435
01:03:28,570 --> 01:03:30,005
where they would never fit.

1436
01:03:30,038 --> 01:03:34,110
These fissures are only about
20 to 30 centimeters wide.

1437
01:03:35,477 --> 01:03:38,581
One more video here,
we're showing a quadrotor

1438
01:03:38,614 --> 01:03:42,151
that's able to land on
the side of a building.

1439
01:03:42,184 --> 01:03:44,687
We use a quadrotor because
we have an atmosphere here.

1440
01:03:44,720 --> 01:03:47,489
If you're in space, you
might have a propulsive robot

1441
01:03:47,522 --> 01:03:49,325
like the SPHERES robot.

1442
01:03:49,358 --> 01:03:51,560
We're making a new version
of that called Astrobee

1443
01:03:51,593 --> 01:03:53,495
up at Ames Research Center.

1444
01:03:53,528 --> 01:03:55,798
You could use a gripper
like this to attach yourself

1445
01:03:55,831 --> 01:03:58,400
to dock to the space
station or a satellite,

1446
01:03:58,433 --> 01:04:00,603
hang out for a while,
save your propellant,

1447
01:04:00,636 --> 01:04:02,638
and then take off again.

1448
01:04:04,973 --> 01:04:08,143

And I think this is my
last set of slides here.

1449
01:04:08,176 --> 01:04:11,747
I just want to voice
how fun a job this is.

1450
01:04:12,981 --> 01:04:14,550
What a toy shop we seem to have.

1451
01:04:14,583 --> 01:04:17,019
I know my garage at
home will never be

1452
01:04:17,052 --> 01:04:20,322
as full as my lab is
here with equipment.

1453
01:04:20,355 --> 01:04:22,625
So we've gotten a lot of
support from our section

1454
01:04:22,658 --> 01:04:27,196
as well as the JPL leadership
to make these things happen.

1455
01:04:27,229 --> 01:04:29,899
So this is where we
spend a lot of our time.

1456
01:04:29,932 --> 01:04:32,768
We also spend a lot of time
here in the machine shop.

1457
01:04:32,801 --> 01:04:35,137
Every once in a while, we
go to the very high-tech

1458
01:04:35,170 --> 01:04:39,208
facilities here at JPL to test

in a space-like environment.

1459
01:04:39,241 --> 01:04:40,943
And as you know,
on the good days,

1460
01:04:40,976 --> 01:04:44,847
I get to have a little fun
inside the zero G airplane

1461
01:04:44,880 --> 01:04:48,784
or have a lot of fun out in
the field with the robots.

1462
01:04:48,817 --> 01:04:51,887
And of course part of
NASA's mission is outreach,

1463
01:04:51,920 --> 01:04:55,224
and so it's always great
fun to do talks like this

1464
01:04:55,257 --> 01:04:58,994
and get to share our
work with the public.

1465
01:04:59,027 --> 01:05:00,696
So that's it.

1466
01:05:00,729 --> 01:05:03,165
I think a few people
in here have worked on

1467
01:05:03,198 --> 01:05:05,467
some of what I've shown,
so I'd ask those people

1468
01:05:05,500 --> 01:05:07,970
to also sort of
stand up and receive

1469
01:05:08,003 --> 01:05:10,639
a round of applause
along with me.

1470
01:05:10,672 --> 01:05:12,675
And I'll be happy to take
some questions, as well.

1471
01:05:12,708 --> 01:05:13,909
Thank you very much.

1472
01:05:13,942 --> 01:05:16,946
(audience applause)

1473
01:05:25,687 --> 01:05:27,289
It appears my team
is either too shy

1474
01:05:27,322 --> 01:05:28,991
or they didn't
wanna come tonight.

1475
01:05:29,024 --> 01:05:30,693
(audience laughing)

1476
01:05:30,726 --> 01:05:32,528
Yeah, so for questions,
if we can have you go

1477
01:05:32,561 --> 01:05:34,196
to the microphone
in the middle there

1478
01:05:34,229 --> 01:05:38,401
just so folks online can
hear the question, as well.

1479
01:05:42,537 --> 01:05:46,141

- Now I was just wondering
if the hooks wear out,

1480
01:05:46,174 --> 01:05:48,711
get blunt, become less
effective over time.

1481
01:05:48,744 --> 01:05:51,080
- Yeah, that's a
excellent question.

1482
01:05:51,113 --> 01:05:53,382
The hooks do wear out over time.

1483
01:05:53,415 --> 01:05:55,084
For the Asteroid
Redirect Mission,

1484
01:05:55,117 --> 01:05:57,419
we only have to grip
the boulder once.

1485
01:05:57,452 --> 01:05:59,154
Where if we fail,
we have the ability

1486
01:05:59,187 --> 01:06:02,391
to try two more attempts,
so they don't really

1487
01:06:02,424 --> 01:06:04,960
wear out over that
length of time.

1488
01:06:04,993 --> 01:06:06,462
The way they wear out, though,

1489
01:06:06,495 --> 01:06:08,731
is if you yank them
off the surface.

1490
01:06:08,764 --> 01:06:12,835
So they only really wear
quickly in a failure case.

1491
01:06:12,868 --> 01:06:14,803
If you're just gripping
and then releasing

1492
01:06:14,836 --> 01:06:17,706
during the normal operation,
they wear very slowly.

1493
01:06:17,739 --> 01:06:21,043
And we've done thousands of
cycles of that kind of grip.

1494
01:06:21,076 --> 01:06:24,780
But when we try and test the
max force that they hold,

1495
01:06:24,813 --> 01:06:28,484
they do dull over the
course of 10, 20 cycles.

1496
01:06:28,517 --> 01:06:29,418
Yeah, yeah.

1497
01:06:31,153 --> 01:06:33,822
- Question, did you think
about the possibility

1498
01:06:33,855 --> 01:06:37,559
of a sooty or gritty or
even oily contaminants

1499
01:06:37,592 --> 01:06:39,161
on the surface of some
of the aluminum objects

1500
01:06:39,194 --> 01:06:41,830
that the gecko adhesive
was designed to move?

1501
01:06:41,863 --> 01:06:43,866
- Yeah, that's a good
question, as well.

1502
01:06:43,899 --> 01:06:47,736
So the surface matters a
lot for the gecko adhesives.

1503
01:06:47,769 --> 01:06:49,972
So the smoother the better.

1504
01:06:51,139 --> 01:06:52,374
Because we don't
have all of that

1505
01:06:52,407 --> 01:06:55,911
intricate hierarchy
that the animal has,

1506
01:06:55,944 --> 01:06:58,680
we can only grip
pretty smooth surfaces.

1507
01:06:58,713 --> 01:07:00,849
And then the dirtiness
of that surface

1508
01:07:00,882 --> 01:07:05,888
or if it's oily or wet will
also degrade the performance.

1509
01:07:05,921 --> 01:07:07,856
You don't see that problem
as much with geckos

1510

01:07:07,889 --> 01:07:10,192
because they're able to
use a stiffer material,

1511
01:07:10,225 --> 01:07:12,061
and so they're more
resilient to dust

1512
01:07:12,094 --> 01:07:13,796
and debris and things like that.

1513
01:07:13,829 --> 01:07:16,598
Good news is in space,
the surfaces are generally

1514
01:07:16,631 --> 01:07:20,702
much cleaner than they are
in our lab, which is a mess.

1515
01:07:20,735 --> 01:07:23,472
(laughing) Yeah.

1516
01:07:25,807 --> 01:07:28,977
- A number of the
robots that climbed up

1517
01:07:29,010 --> 01:07:31,847
a vertical surface had
a tail, and I wonder

1518
01:07:31,880 --> 01:07:33,515
if there's a function to that.

1519
01:07:33,548 --> 01:07:35,484
- Yeah, you guys
have great questions.

1520
01:07:35,517 --> 01:07:37,753
A tail is very important.

1521
01:07:37,786 --> 01:07:40,222
If all you have is the
two wheels in the front,

1522
01:07:40,255 --> 01:07:41,857
the robot's gonna spin around.

1523
01:07:41,890 --> 01:07:43,826
So the tail reacts the moment

1524
01:07:43,859 --> 01:07:45,994
that keeps you
from falling back.

1525
01:07:46,027 --> 01:07:47,196
And tails are actually
really important

1526
01:07:47,229 --> 01:07:49,765
in biology, as
well, for balance.

1527
01:07:49,798 --> 01:07:53,402
But there's a, I didn't
show the video, but geckos-

1528
01:07:53,435 --> 01:07:55,003
we've worked with some
folks that do some

1529
01:07:55,036 --> 01:07:58,107
interesting things like
put slippery surfaces

1530
01:07:58,140 --> 01:08:00,275
and then make the geckos
try and climb across them.

1531
01:08:00,308 --> 01:08:01,510

So these are great videos.

1532
01:08:01,543 --> 01:08:02,878
You watch the gecko
climbing up the wall,

1533
01:08:02,911 --> 01:08:04,446
and then all of a
sudden it's like

1534
01:08:04,479 --> 01:08:06,582
it's stepped on a banana,
and it starts slipping.

1535
01:08:06,615 --> 01:08:08,851
And what they do at that
point, is they actually

1536
01:08:08,884 --> 01:08:11,920
push their tail as hard
as they can into the wall.

1537
01:08:11,953 --> 01:08:14,756
So they're falling backwards,
and they use the tail

1538
01:08:14,789 --> 01:08:18,660
as a self righting mechanism
to regain their grip.

1539
01:08:18,693 --> 01:08:21,697
So, yeah, tails are
really critical.

1540
01:08:21,730 --> 01:08:23,365
What you see on ours
are passive tails.

1541
01:08:23,398 --> 01:08:25,734
They're just a pole that

reacts to the moment.

1542
01:08:25,767 --> 01:08:28,737
I think in the future, we'd
like to make those tails active

1543
01:08:28,770 --> 01:08:31,907
the same way an animal's
tail is active and able to do

1544
01:08:31,940 --> 01:08:36,112
those kinds of fall responses
and things like that.

1545
01:08:40,248 --> 01:08:41,517
Yeah, other questions.

1546
01:08:41,550 --> 01:08:43,752
- Great talk, thank you.
- Yeah.

1547
01:08:43,785 --> 01:08:45,854
- So I was wondering,
what about the timelines

1548
01:08:45,887 --> 01:08:48,657
for these projects or
the groups of people?

1549
01:08:48,690 --> 01:08:50,225
Like how many work on these,

1550
01:08:50,258 --> 01:08:53,195
especially in the earlier
versions of rapid prototypes?

1551
01:08:53,228 --> 01:08:56,698
- Yeah, so the projects
will range in duration

1552
01:08:56,731 --> 01:08:59,134
from a few months, where
you're just trying to show

1553
01:08:59,167 --> 01:09:03,372
the first version of the
prototype, and to a few years,

1554
01:09:03,405 --> 01:09:06,375
where you really have some
higher level objectives.

1555
01:09:06,408 --> 01:09:08,577
The Asteroid Redirect
Mission we started

1556
01:09:08,610 --> 01:09:10,913
about a year and a
half ago, formally,

1557
01:09:10,946 --> 01:09:15,250
and that's currently
targeting to launch in 2021.

1558
01:09:15,283 --> 01:09:16,718
So that's a very long timeline.

1559
01:09:16,751 --> 01:09:18,153
We have to deliver our hardware

1560
01:09:18,186 --> 01:09:21,190
in a year and a half
before the actual launch.

1561
01:09:21,223 --> 01:09:25,260
But that gives you a
sense of the timelines.

1562
01:09:25,293 --> 01:09:28,530

When you're at a lower
level of development,

1563
01:09:28,563 --> 01:09:30,832
those prototypes can
happen very quickly.

1564
01:09:30,865 --> 01:09:32,067
Couple of weeks.

1565
01:09:32,100 --> 01:09:34,636
And you can build them
maybe one or two people.

1566
01:09:34,669 --> 01:09:36,872
As you get up to a
more complex robot,

1567
01:09:36,905 --> 01:09:40,342
the rock climbing robots,
it's a team of about five.

1568
01:09:40,375 --> 01:09:42,377
The asteroid grippers,
right now we're a team

1569
01:09:42,410 --> 01:09:45,214
of about seven, but that's
gonna grow to a peak

1570
01:09:45,247 --> 01:09:48,517
of about 12 or 13 of
us, I think, yeah.

1571
01:09:49,484 --> 01:09:50,953
Yeah.

1572
01:09:50,986 --> 01:09:53,222
- Can you talk a little bit
about cable tensed structures

1573
01:09:53,255 --> 01:09:55,357
that are pulled through
tubes as opposed to

1574
01:09:55,390 --> 01:09:57,693
stepper motor
actuated rigid arms?

1575
01:09:57,726 --> 01:09:59,394
- Yeah, sure.

1576
01:09:59,427 --> 01:10:03,599
So we do use cables to
actuate parts of our grippers

1577
01:10:04,766 --> 01:10:06,602
and other parts of the robots.

1578
01:10:06,635 --> 01:10:09,438
Cables are nice because they
only act in one direction.

1579
01:10:09,471 --> 01:10:12,274
So you can pull on
them and have tension,

1580
01:10:12,307 --> 01:10:14,209
but when, for
instance, those fingers

1581
01:10:14,242 --> 01:10:17,312
flop down on the surface,
if one flops down early,

1582
01:10:17,345 --> 01:10:20,449
the cable just goes slack
as opposed to a bar,

1583

01:10:20,482 --> 01:10:22,384
which would get jammed.

1584
01:10:23,551 --> 01:10:25,087
Now the downside is
that you gotta do

1585
01:10:25,120 --> 01:10:29,024
cable management and
routing all those cables,

1586
01:10:29,057 --> 01:10:30,559
making sure they're
the right length.

1587
01:10:30,592 --> 01:10:33,128
I have learned all my Boy
Scout knots late in life

1588
01:10:33,161 --> 01:10:35,664
dealing with those
kinds of systems.

1589
01:10:35,697 --> 01:10:37,699
So it's always an
engineering trade

1590
01:10:37,732 --> 01:10:40,502
between what you're trying
to have the system do

1591
01:10:40,535 --> 01:10:44,106
and what you're
engineering parameters are.

1592
01:10:45,707 --> 01:10:47,776
Another thing, maybe you
were asking about this,

1593
01:10:47,809 --> 01:10:49,311

is cables can be used to change

1594
01:10:49,344 --> 01:10:51,246
a stiffness of a
structure sometimes,

1595
01:10:51,279 --> 01:10:53,482
those are called
tensegrity robots.

1596
01:10:53,515 --> 01:10:56,418
Actually, you're human body
is a tensegrity structure.

1597
01:10:56,451 --> 01:10:59,121
The tendons and
muscles are in tension

1598
01:10:59,154 --> 01:11:02,257
keeping your stiffness different

1599
01:11:02,290 --> 01:11:05,093
than if you were just
standing on your bones alone.

1600
01:11:05,126 --> 01:11:06,595
So some folks are
working in robotics

1601
01:11:06,628 --> 01:11:09,431
where they're using cables
and tensioning those cables

1602
01:11:09,464 --> 01:11:12,501
to try and give the robot a
different level of stiffness.

1603
01:11:12,534 --> 01:11:16,271
In our lab, we haven't
really worked on that yet.

1604
01:11:16,304 --> 01:11:17,673
There's some ideas
floating around,

1605
01:11:17,706 --> 01:11:20,642
but we're not going down
that path right now.

1606
01:11:20,675 --> 01:11:23,312
- And on an extension
for the cable concept,

1607
01:11:23,345 --> 01:11:24,446
how are they actuated?

1608
01:11:24,479 --> 01:11:27,215
Is it solenoids or is it cams?

1609
01:11:27,248 --> 01:11:29,785
And if it is solenoids,
how would that function in

1610
01:11:29,818 --> 01:11:33,555
magnetically active environments
like the Van Allen belt?

1611
01:11:33,588 --> 01:11:38,126
- So none of what you
saw today was a solenoid.

1612
01:11:38,159 --> 01:11:40,829
In prototyping, a lot of
times we use servo motors

1613
01:11:40,862 --> 01:11:43,032
or just brushed DC motors.

1614
01:11:44,165 --> 01:11:45,500

A lot of times, as
well, we're trying to do

1615
01:11:45,533 --> 01:11:49,738
underactuation so when
those carriages lift up,

1616
01:11:49,771 --> 01:11:52,874
that's one motor that's
powering all 16 of those, right?

1617
01:11:52,907 --> 01:11:54,443
We're just pulling
on a plate that has

1618
01:11:54,476 --> 01:11:57,646
all of those cables
attached to it.

1619
01:11:57,679 --> 01:12:01,283
In flight, a lot of times
we use brushless DC motors

1620
01:12:01,316 --> 01:12:03,585
because the brushes
can create debris

1621
01:12:03,618 --> 01:12:07,022
and don't work quite
as well in vacuum.

1622
01:12:07,055 --> 01:12:08,790
So we use those as
well, sometimes.

1623
01:12:08,823 --> 01:12:10,759
It's sort of a-

1624
01:12:10,792 --> 01:12:14,963
each job requires maybe a

different consideration.

1625
01:12:15,997 --> 01:12:17,166
Yeah.
- Thanks.

1626
01:12:19,634 --> 01:12:21,737
- It's too tall for me, okay.

1627
01:12:21,770 --> 01:12:25,540
Hi, this is very exciting,
so thank you for this talk.

1628
01:12:25,573 --> 01:12:28,243
I was wondering what
the current use rate

1629
01:12:28,276 --> 01:12:31,847
of 3D printing is for you
guys, and is there a plan

1630
01:12:31,880 --> 01:12:35,584
or a roadmap to increase
that to a certain percentage,

1631
01:12:35,617 --> 01:12:37,786
whether it be for
efficiency or just

1632
01:12:37,819 --> 01:12:41,123
ease of building maybe
what doesn't exist?

1633
01:12:41,156 --> 01:12:43,092
- Yeah, so I would say-

1634
01:12:44,526 --> 01:12:46,828
Well we have, let's see,
we've gone through probably

1635
01:12:46,861 --> 01:12:51,700
12 or 15 different 3D printers
in the last five years or so.

1636
01:12:51,733 --> 01:12:55,137
We bring in some of the low
cost hobby kind of grade ones

1637
01:12:55,170 --> 01:12:58,607
that we use for quick,
dirty prototypes,

1638
01:12:58,640 --> 01:13:00,642
and we turn our
students loose on those.

1639
01:13:00,675 --> 01:13:03,745
We also have some high-end
printers that we call them

1640
01:13:03,778 --> 01:13:07,215
the Ferrari because the price
tag is kind of equivalent.

1641
01:13:07,248 --> 01:13:11,420
But across the board, those
printers run every day for us.

1642
01:13:11,453 --> 01:13:16,224
So at times during the summer,
which is our busiest season,

1643
01:13:16,257 --> 01:13:19,861
we haves queues of people
waiting to print parts.

1644
01:13:19,894 --> 01:13:23,331
So in a prototyping phase,
they're in use constantly.

1645
01:13:23,364 --> 01:13:25,267
And we've tried to
open up that lab space

1646
01:13:25,300 --> 01:13:27,969
to the broader JPL
community, as well.

1647
01:13:28,002 --> 01:13:29,905
So we have people from
all different sections,

1648
01:13:29,938 --> 01:13:33,775
all different departments
coming by to print parts

1649
01:13:33,808 --> 01:13:37,179
because they have
a need for them.

1650
01:13:37,212 --> 01:13:39,948
So the adoption rate
has been really quick.

1651
01:13:39,981 --> 01:13:42,384
I think it's gonna
continue to grow.

1652
01:13:42,417 --> 01:13:45,921
One area that we haven't
really moved into yet

1653
01:13:45,954 --> 01:13:48,790
but I think is coming
is metal 3D printing.

1654
01:13:48,823 --> 01:13:50,592
So we have filament
style printers,

1655
01:13:50,625 --> 01:13:54,129
we have liquid UV resin
kinds of printers,

1656
01:13:55,497 --> 01:13:58,300
and I think the metal
printers are coming next.

1657
01:13:58,333 --> 01:14:00,068
We've outsourced some parts.

1658
01:14:00,101 --> 01:14:02,437
We use local shops and
vendors all the time, as well.

1659
01:14:02,470 --> 01:14:06,007
So we've had some titanium
printed parts that we've used,

1660
01:14:06,040 --> 01:14:08,977
but I think JPL is
gonna get on board

1661
01:14:09,010 --> 01:14:11,580
and get some of our own
machines there soon, as well.

1662
01:14:11,613 --> 01:14:14,916
People are actually looking
into flying 3D printed parts

1663
01:14:14,949 --> 01:14:16,418
as part of the spacecraft.

1664
01:14:16,451 --> 01:14:19,988
So it makes a lot of sense,
and I think it's gonna happen.

1665
01:14:20,021 --> 01:14:21,023

- Thank you.

1666
01:14:26,194 --> 01:14:29,498
- It looked like a number of
your robots were autonomous,

1667
01:14:29,531 --> 01:14:32,000
weren't any cables
attached or anything.

1668
01:14:32,033 --> 01:14:33,401
Could you talk briefly
about what kind of

1669
01:14:33,434 --> 01:14:36,238
controllers they have on
board to have direction

1670
01:14:36,271 --> 01:14:38,673
and move the limbs
and all of that?

1671
01:14:38,706 --> 01:14:43,011
- Yeah, so autonomy is
an interesting thing.

1672
01:14:43,044 --> 01:14:45,680
We don't think of
autonomy as on or off,

1673
01:14:45,713 --> 01:14:47,716
we think of it as
a slider between

1674
01:14:47,749 --> 01:14:50,986
fully teleoperated
and fully autonomous.

1675
01:14:51,019 --> 01:14:52,554
And so on some of the robots,

1676
01:14:52,587 --> 01:14:54,155
that slider's kind
of in the middle.

1677
01:14:54,188 --> 01:14:56,091
If you're climbing up a
wall, and you're trying

1678
01:14:56,124 --> 01:14:58,927
to steer looking at a
camera, turns out the wall

1679
01:14:58,960 --> 01:15:01,730
looks the same whether
you're 15 degrees to the left

1680
01:15:01,763 --> 01:15:03,465
or 15 degrees to the right.

1681
01:15:03,498 --> 01:15:05,867
So what we do is
we augment the user

1682
01:15:05,900 --> 01:15:09,137
by steering to match the
gravity vector, right?

1683
01:15:09,170 --> 01:15:11,006
So this is sort of autonomy,

1684
01:15:11,039 --> 01:15:15,710
but it's also still being
controlled by an operator.

1685
01:15:15,743 --> 01:15:18,513
On the further side for
the rock climbing robots,

1686

01:15:18,546 --> 01:15:20,882
we are trying to make
that much more autonomous

1687
01:15:20,915 --> 01:15:24,252
where we give it waypoints that
are maybe a few meters ahead

1688
01:15:24,285 --> 01:15:28,156
of where it is, and it
decides how to move its limbs

1689
01:15:28,189 --> 01:15:30,992
and where the good
places to grip are.

1690
01:15:31,025 --> 01:15:34,696
Turns out that a person
trying to sort of joystick

1691
01:15:34,729 --> 01:15:38,800
a seven degree of freedom limb
is actually not very good.

1692
01:15:38,833 --> 01:15:42,337
It's too complex for you
to work out in your head

1693
01:15:42,370 --> 01:15:44,940
which motor has to
move at which time.

1694
01:15:44,973 --> 01:15:46,207
And you don't have
enough buttons

1695
01:15:46,240 --> 01:15:48,410
on the controller
to do it, anyways.

1696

01:15:48,443 --> 01:15:50,879
And so we try and use
a lot more autonomy,

1697
01:15:50,912 --> 01:15:54,516
move that slider closer to
a fully autonomous state

1698
01:15:54,549 --> 01:15:57,953
for some of the rock
climbing robots.

1699
01:15:57,986 --> 01:16:00,488
- And what do you use on board
for a processing satellite,

1700
01:16:00,521 --> 01:16:01,890
do we know?

1701
01:16:01,923 --> 01:16:03,391
- So, no, so the
rock climbing robot

1702
01:16:03,424 --> 01:16:07,062
right now has two
brains, if you will.

1703
01:16:07,095 --> 01:16:10,932
It's got a low brain
that's a PC/104 stack.

1704
01:16:10,965 --> 01:16:12,200
So that's a bunch of cards.

1705
01:16:12,233 --> 01:16:15,136
It's actually pretty old
electronics technology.

1706
01:16:15,169 --> 01:16:19,341
And then it has an Intel NUC,

which is a much more powerful

1707
01:16:19,374 --> 01:16:23,278
computer that's doing the higher
level computer vision work

1708
01:16:23,311 --> 01:16:25,947
and the trajectory
generation, and then those two

1709
01:16:25,980 --> 01:16:28,249
have to talk to each other.

1710
01:16:28,282 --> 01:16:31,753
So the lower brain handles
make the motor spin,

1711
01:16:31,786 --> 01:16:35,523
and that Intel computer handles
the where do I put my foot

1712
01:16:35,556 --> 01:16:39,160
and how do I move
all of my joints.

1713
01:16:39,193 --> 01:16:40,762
- Thank you.
- Sure.

1714
01:16:44,432 --> 01:16:45,533
- Hi.
- Hello.

1715
01:16:46,968 --> 01:16:51,239
- So I have questions about
the adhesive gecko robots.

1716
01:16:51,272 --> 01:16:52,774
- Sure.
- So you guys are

1717
01:16:52,807 --> 01:16:56,344
planning to deploy that on
a mission to Mars, right?

1718
01:16:56,377 --> 01:16:58,213
So my question is that

1719
01:17:00,314 --> 01:17:03,051
the weathers on Mars
are much harsher

1720
01:17:03,084 --> 01:17:05,854
than it is here on Earth,
have you guys thought about

1721
01:17:05,887 --> 01:17:08,990
something like
how to tackle that

1722
01:17:09,023 --> 01:17:12,193
when it hit a storm or
something like that?

1723
01:17:12,226 --> 01:17:14,529
- Yeah, so the
environment on Mars

1724
01:17:14,562 --> 01:17:16,732
is obviously very extreme.

1725
01:17:19,033 --> 01:17:20,235
It's funny that our group name

1726
01:17:20,268 --> 01:17:22,003
is Extreme Environment Robotics.

1727
01:17:22,036 --> 01:17:23,238
You might think

that the entire lab

1728
01:17:23,271 --> 01:17:26,307
is really doing extreme
environment robotics.

1729
01:17:26,340 --> 01:17:27,976
So it's a consideration.

1730
01:17:28,009 --> 01:17:30,045
In the prototyping
phase, we haven't really

1731
01:17:30,078 --> 01:17:34,349
been too concerned about
the thermal environment

1732
01:17:34,382 --> 01:17:37,852
or protecting ourselves
from dust and debris,

1733
01:17:37,885 --> 01:17:41,022
but as that robot
matures, we would bring in

1734
01:17:41,055 --> 01:17:44,359
all of those folks from
JPL who are really expert

1735
01:17:44,392 --> 01:17:47,495
at managing the cold
temperatures and the

1736
01:17:47,528 --> 01:17:50,031
hot temperatures and
managing the dust storms

1737
01:17:50,064 --> 01:17:52,100
and some of those
sorts of things.

1738
01:17:52,133 --> 01:17:55,603
And I don't think there's
any critical limitations

1739
01:17:55,636 --> 01:17:58,306
for the rock climbing
robots to operate

1740
01:17:58,339 --> 01:18:00,141
on the surface of Mars.

1741
01:18:00,174 --> 01:18:02,243
The gecko adhesives are
really tailored more

1742
01:18:02,276 --> 01:18:05,380
to smooth surfaces, so we
wouldn't use those on Mars.

1743
01:18:05,413 --> 01:18:07,782
We'd use the gecko
adhesives in orbit

1744
01:18:07,815 --> 01:18:10,118
to grapple satellites
and operate maybe

1745
01:18:10,151 --> 01:18:13,221
on the sort of carrier ship
that would go back and forth

1746
01:18:13,254 --> 01:18:15,890
between Mars and
Earth but not actually

1747
01:18:15,923 --> 01:18:19,428
on the surface where
it's dirty and rough.

1748
01:18:21,662 --> 01:18:23,198
- Alright, thank you.
- You're welcome.

1749
01:18:23,231 --> 01:18:26,234
I think we have a couple
questions from online, maybe.

1750
01:18:26,267 --> 01:18:28,236
And these have been screened,

1751
01:18:28,269 --> 01:18:30,038
so these are the
best ones, I think.

1752
01:18:30,071 --> 01:18:31,573
(audience laughing)

1753
01:18:31,606 --> 01:18:34,109
The question here is what are
the major challenges in moving

1754
01:18:34,142 --> 01:18:38,113
the grippers from field
tests to space flight tests?

1755
01:18:38,146 --> 01:18:40,515
That's a great question.

1756
01:18:40,548 --> 01:18:42,917
Some of the challenges
are technical

1757
01:18:42,950 --> 01:18:46,020
like figuring out
how to make it robust

1758
01:18:46,053 --> 01:18:48,556
across all of the

different rock types.

1759
01:18:48,589 --> 01:18:51,793
So it's easy when you're
developing something in the lab

1760
01:18:51,826 --> 01:18:53,495
to kind of design it to work on

1761
01:18:53,528 --> 01:18:55,363
whatever you have in the lab.

1762
01:18:55,396 --> 01:18:56,998
You take it out into the
field and you realize,

1763
01:18:57,031 --> 01:18:59,033
oh, this rock is actually
a little different.

1764
01:18:59,066 --> 01:19:02,270
We're going to have to go
back and fix some things.

1765
01:19:02,303 --> 01:19:05,140
So some of the technical
challenges are in making it

1766
01:19:05,173 --> 01:19:09,077
robust, making sure it
doesn't break over time.

1767
01:19:09,110 --> 01:19:11,246
But some of the other
challenges to moving

1768
01:19:11,279 --> 01:19:15,717
from the lab to space flight
are actually programmatic.

1769
01:19:15,750 --> 01:19:18,419
You need to be in the right
place at the right time,

1770
01:19:18,452 --> 01:19:21,456
so if you're developing a
technology that's really tuned

1771
01:19:21,489 --> 01:19:24,626
for Venus, and the next
mission is going to Mars,

1772
01:19:24,659 --> 01:19:27,395
you've got a mismatch
there, and so there's always

1773
01:19:27,428 --> 01:19:31,600
a little bit of awareness and
strategy that NASA and JPL

1774
01:19:33,234 --> 01:19:35,737
is trying to stay on top of
to make sure we're developing

1775
01:19:35,770 --> 01:19:39,508
the right technologies
for the next missions.

1776
01:19:40,775 --> 01:19:43,278
So some of the
challenges can be of that

1777
01:19:43,311 --> 01:19:46,548
more personal or
non-technical variety.

1778
01:19:49,083 --> 01:19:51,186
I guess the other one,
which is a big driver,

1779
01:19:51,219 --> 01:19:55,557
is testing, the costs of
doing environmental testing

1780
01:19:55,590 --> 01:19:59,761
and really validating your
technology can be very high.

1781
01:19:59,794 --> 01:20:03,464
So to do that on an R&D budget
can be a real challenge.

1782
01:20:03,497 --> 01:20:05,233
And sometimes there's a mismatch

1783
01:20:05,266 --> 01:20:07,735
between what a mission
is willing to pay for

1784
01:20:07,768 --> 01:20:10,872
and what the technology
program is willing to pay for

1785
01:20:10,905 --> 01:20:12,907
where you have to try and
prove that you're ready

1786
01:20:12,940 --> 01:20:15,743
for the mission, but in
order to do that testing,

1787
01:20:15,776 --> 01:20:19,013
you need the dollars that are
associated with the mission.

1788
01:20:19,046 --> 01:20:23,484
So sometimes, it's trying to
scrap together a story that

1789

01:20:23,517 --> 01:20:27,755
really proves that it's gonna
work in that environment.

1790
01:20:27,788 --> 01:20:30,292
So the second question here is

1791
01:20:31,759 --> 01:20:35,363
are AI and machine learning
technologies in use here?

1792
01:20:35,396 --> 01:20:36,631
And if so, how?

1793
01:20:37,865 --> 01:20:41,102
So the answer, AI
and machine learning,

1794
01:20:42,336 --> 01:20:45,373
they are definitely
in use here at JPL.

1795
01:20:45,406 --> 01:20:47,375
In the robots I
showed you here today,

1796
01:20:47,408 --> 01:20:51,913
we're not really doing much
machine learning or AI.

1797
01:20:51,946 --> 01:20:55,383
The one exception to that,
is we're trying to train

1798
01:20:55,416 --> 01:20:59,621
the rock climbing robot on
what is a good place to grip,

1799
01:20:59,654 --> 01:21:02,991
and so we've just started

collecting lots and lots

1800
01:21:03,024 --> 01:21:07,095
of 3D models of different rock
faces, and we're, by hand,

1801
01:21:07,128 --> 01:21:09,464
highlighting these are
good places to grip,

1802
01:21:09,497 --> 01:21:11,799
these are bad places to grip,
and then we're gonna feed

1803
01:21:11,832 --> 01:21:16,537
that into a program that
will learn, hopefully,

1804
01:21:16,570 --> 01:21:21,276
from those examples where
those good places to grip are.

1805
01:21:21,309 --> 01:21:24,245
That's work that's just
getting under way now.

1806
01:21:24,278 --> 01:21:26,848
But there's a lot more complex
machine learning and AI

1807
01:21:26,881 --> 01:21:30,118
that's happening in
other projects at JPL.

1808
01:21:30,151 --> 01:21:33,221
So I'd encourage you to go
to the JPL Robotics website,

1809
01:21:33,254 --> 01:21:35,189
and there's lots of videos

of some other robots

1810
01:21:35,222 --> 01:21:38,660
that really emphasize
those technologies.

1811
01:21:40,094 --> 01:21:43,865
So that's it, and I'll stick
around up front if people have-

1812
01:21:44,999 --> 01:21:46,634
well, we'll take one
more question, I guess.

1813
01:21:46,667 --> 01:21:47,468
- Thank you.
- Go ahead.

1814
01:21:47,501 --> 01:21:48,970
- I appreciate it.

1815
01:21:49,003 --> 01:21:53,008
On the ARM project, when you
bring the boulder off the comet

1816
01:21:55,042 --> 01:21:58,313
and you bring it to the
Moon and put it in orbit

1817
01:21:58,346 --> 01:22:02,884
around the Moon, you said that
you were gonna let companies

1818
01:22:02,917 --> 01:22:04,652
possibly go up there
and practice mining

1819
01:22:04,685 --> 01:22:06,655
and that sort of thing.

1820
01:22:08,389 --> 01:22:11,225
Is that something that
we'd be able to see

1821
01:22:11,258 --> 01:22:12,928
through a telescope?

1822
01:22:14,128 --> 01:22:17,865
I know you said it's as
big as a SUV, possibly,

1823
01:22:17,898 --> 01:22:20,468
in orbit around the Moon,
and I was just wondering

1824
01:22:20,501 --> 01:22:23,604
if that would be like
something we'd be able to see,

1825
01:22:23,637 --> 01:22:25,373
and how big is the orbit,

1826
01:22:25,406 --> 01:22:27,342
and how long would
it take to go around?

1827
01:22:27,375 --> 01:22:31,079
- Yeah, so after we pull the
boulder from the asteroid,

1828
01:22:31,112 --> 01:22:32,847
we'll put it in
a, what's called a

1829
01:22:32,880 --> 01:22:36,084
retrograde orbit around the
Moon, so it's very stable.

1830
01:22:36,117 --> 01:22:40,488

And it'll be up there
for hundreds of years.

1831
01:22:40,521 --> 01:22:43,825
Now, I don't think
it'll be large enough

1832
01:22:43,858 --> 01:22:46,260
to see with most telescopes.

1833
01:22:46,293 --> 01:22:48,963
I think you might be able
to see a point source

1834
01:22:48,996 --> 01:22:51,499
that, yeah, there's a signal or

1835
01:22:53,300 --> 01:22:55,103
certainly we're going to be
talking to the spacecraft,

1836
01:22:55,136 --> 01:22:57,605
but I don't think,
optically, you're probably

1837
01:22:57,638 --> 01:22:59,707
going to be able to see that.

1838
01:22:59,740 --> 01:23:03,011
But that's my 90%
confidence answer,

1839
01:23:03,044 --> 01:23:04,979
I'm not for sure on that.

1840
01:23:05,012 --> 01:23:06,681
- [Man] Put a reflector on it.

1841
01:23:06,714 --> 01:23:09,250

- Yeah.
(audience laughing)

1842
01:23:09,283 --> 01:23:11,719
But you'll get great videos
when the crew come and dock

1843
01:23:11,752 --> 01:23:15,757
with that spacecraft and the
boulder, and we'll probably see

1844
01:23:15,790 --> 01:23:19,961
all of that happening in near
real time down here on Earth.

1845
01:23:21,028 --> 01:23:22,897
So that'll be very exciting.

1846
01:23:22,930 --> 01:23:24,832
Thank you again for
coming, it was my pleasure.

1847
01:23:24,865 --> 01:23:27,869
(audience applause)