1
00:00:02,700 --> 00:00:16,100
[music playing]

2
00:00:16,100 --> 00:00:22,600
- Welcome to the 2016
NASA Ames Summer Series.

3
00:00:22,600 --> 00:00:24,130
Hmm.

4
00:00:24,130 --> 00:00:26,870
[laughter]

5
00:00:26,870 --> 00:00:30,170
Evolution in front of us.

6
00:00:30,170 --> 00:00:33,930
So nature evolved solutions

7
00:00:33,930 --> 00:00:38,170
to various applications
for thousands of years,

8
00:00:38,170 --> 00:00:41,930
and thus, provides templates
to mimic

9
00:00:41,930 --> 00:00:44,830
for our own applications.

10
00:00:44,830 --> 00:00:47,970
But when we try to mimic,

11
00:00:47,970 --> 00:00:52,330
we also gain insight
on the original.

12
00:00:52,330 --> 00:00:54,600

Today's seminar entitled

13
00:00:54,600 --> 00:00:57,070
"SUPERball: A Biological--

14
00:00:57,070 --> 00:01:01,000
A Biologically Inspired Robot
for Planetary Exploration"

15
00:01:01,000 --> 00:01:07,300
will be given by
Mr. Vytas SunSpiral.

16
00:01:07,300 --> 00:01:11,870
Mr. SunSpiral received a BA
in symbolic systems

17
00:01:18,730 --> 00:01:13,870
from Stanford University

18
00:01:18,730 --> 00:01:23,000
In 1998 he founded Mobot,

19
00:01:23,000 --> 00:01:25,700
which sold the world's first
commercial--

20
00:01:25,700 --> 00:01:32,070
commercially available
autonomous tour guide robot.

21
00:01:32,070 --> 00:01:34,470
He joined Ames in 2002

22
00:01:34,470 --> 00:01:36,670
as a robotic researcher

23
00:01:36,670 --> 00:01:39,130
and is now a principle

investigator

24
00:01:39,130 --> 00:01:41,900
for the Dynamic Tensegrity
Robotic Lab

25
00:01:41,900 --> 00:01:45,000
in the Intelligent Robotic Group
at NASA Ames.

26
00:01:45,000 --> 00:01:48,800
Please join me in welcoming
Vytas SunSpiral.

27
00:01:48,800 --> 00:01:52,500
[applause]

28
00:01:52,500 --> 00:01:55,730
- Thank you, Jacob.

29
00:01:55,730 --> 00:01:57,570
All right.

30
00:01:57,570 --> 00:02:02,900
Let's get the presentation
on the road.

31
00:02:02,900 --> 00:02:09,370
There we go.
This is the one we want.

32
00:02:09,370 --> 00:02:11,330
All right, everybody, hello.

33
00:02:11,330 --> 00:02:12,930
all: Hello.

34
00:02:12,930 --> 00:02:15,570
- Okay, so I'm gonna give you

an initial teaser here

35
00:02:15,570 --> 00:02:18,900
of where we're going
with this story.

36
00:02:18,900 --> 00:02:22,230
This is the sort of NASA vision
of this project,

37
00:02:22,230 --> 00:02:24,530
which is to build a robot
that's so robust,

38
00:02:24,530 --> 00:02:26,030
so compliant and adaptable,

39
00:02:26,030 --> 00:02:27,870
that it can survive landing
on another planet

40
00:02:27,870 --> 00:02:29,800
as if it was its own air bag.

41
00:02:29,800 --> 00:02:32,470
So now you don't need an air bag
and you can explore

42
00:02:32,470 --> 00:02:34,000
in all sorts of new
and interesting ways,

43
00:02:34,000 --> 00:02:36,400
and it has lots of
mission design impacts.

44
00:02:36,400 --> 00:02:39,800
And we will get back to this
in a moment

45
00:02:39,800 --> 00:02:41,770
with a lot more details.

46
00:02:41,770 --> 00:02:44,100
But I wanted to sort of show you
where the--the current state

47
00:02:44,100 --> 00:02:46,830
of the technology
and where we're headed is.

48
00:02:46,830 --> 00:02:51,730
So--but this all started with
my own personal quest originally

49
00:02:51,730 --> 00:02:54,030
to really understand
our intelligence.

50
00:02:54,030 --> 00:02:55,500
You know, as he mentioned,
I came from

51
00:02:55,500 --> 00:02:57,730
the symbolic systems program,
which is really a program

52
00:02:57,730 --> 00:03:00,430
that looked at a lot of
human intelligence,

53
00:03:00,430 --> 00:03:01,770
artificial intelligence,

54
00:03:01,770 --> 00:03:03,930
and--and how complex systems
like that work.

55
00:03:03,930 --> 00:03:06,970

And as I got into this
over the years,

56
00:03:06,970 --> 00:03:10,000
I really started to feel that
you needed to understand

57
00:03:10,000 --> 00:03:12,200
how we move

58
00:03:12,200 --> 00:03:14,370
if you want to understand
how we think.

59
00:03:14,370 --> 00:03:16,100
These two are
very tightly related.

60
00:03:16,100 --> 00:03:19,270
and if you really dive back into
the origins of evolution,

61
00:03:19,270 --> 00:03:23,030
you'll see that
the very first neurons appeared

62
00:03:23,030 --> 00:03:24,830
in order to control motors,

63
00:03:24,830 --> 00:03:26,930
i.e. the first muscles,
early muscles.

64
00:03:26,930 --> 00:03:29,330
So neurons are originally
motor controllers

65
00:03:29,330 --> 00:03:31,100
and then they evolved
on top of that

66
00:03:31,100 --> 00:03:33,030
and evolution happened
on top of that.

67
00:03:33,030 --> 00:03:34,570
And as nature does,

68
00:03:34,570 --> 00:03:36,530
once it figures out
a really good trick,

69
00:03:36,530 --> 00:03:38,270
it figures out how to reuse it
and reapply it

70
00:03:38,270 --> 00:03:39,900
in more and more complex ways.

71
00:03:39,900 --> 00:03:41,270
And so if you want to
understand--

72
00:03:41,270 --> 00:03:43,500
if you--if you start by
understanding how we move

73
00:03:43,500 --> 00:03:45,100
and--and really get that,

74
00:03:45,100 --> 00:03:46,600
then you start seeing
the foundation

75
00:03:46,600 --> 00:03:48,900
for all these other
more complex things we do

76
00:03:48,900 --> 00:03:52,000

like the finer points
of politics and art.

77
00:03:52,000 --> 00:03:54,100
And whether we like burritos
or hamburgers

78
00:03:54,100 --> 00:03:55,830
and all that sort of stuff,
all right?

79
00:03:55,830 --> 00:03:57,270
So it's all related.

80
00:03:57,270 --> 00:04:02,130
So the story that
I'm gonna tell you today

81
00:04:02,130 --> 00:04:04,400
really involves
starting with the brain.

82
00:04:04,400 --> 00:04:05,730
I'll tell you a little bit
about that.

83
00:04:05,730 --> 00:04:06,900
We're gonna start

84
00:04:06,900 --> 00:04:08,600
by tearing apart
a lot of common assumptions,

85
00:04:08,600 --> 00:04:10,400
and that's sort of at the heart
often of science.

86
00:04:10,400 --> 00:04:12,670
To learn new things you have to
often forget old things.

87
00:04:12,670 --> 00:04:14,630
and there's a lot of things
that, you know,

88
00:04:14,630 --> 00:04:17,000
as science progresses,
we're sort of discovering,

89
00:04:17,000 --> 00:04:19,600
and some of it is theoretical
and some of it is proven

90
00:04:19,600 --> 00:04:21,430
and, you know, it's all
kind of there in the mix.

91
00:04:21,430 --> 00:04:23,200
But so we're gonna start
a little bit about the brain.

92
00:04:23,200 --> 00:04:25,670
and then we're gonna dive into
how the body works

93
00:04:25,670 --> 00:04:27,500
and have some maybe

94
00:04:27,500 --> 00:04:29,900
possibly surprising
new insights into that

95
00:04:29,900 --> 00:04:32,570
and that will bring us to
tensegrity structures,

96
00:04:32,570 --> 00:04:37,070
which are a very interesting
form of tensile structure.

97
00:04:37,070 --> 00:04:38,670
And from there,
we'll get to the robots,

98
00:04:38,670 --> 00:04:41,030
and then back to the brain
and the control system

99
00:04:41,030 --> 00:04:43,600
of how we actually move,
and that will really lead us to

100
00:04:43,600 --> 00:04:45,900
some final philosophical
insights.

101
00:04:45,900 --> 00:04:49,070
So diving in.

102
00:04:49,070 --> 00:04:51,070
We generally assume

103
00:04:51,070 --> 00:04:53,170
that the brain is where we do
all the thinking

104
00:04:53,170 --> 00:04:54,670
and all the reasoning
and all the controls

105
00:04:54,670 --> 00:04:57,170
and the motor cortexes where
we drive all of our motion from.

106
00:04:57,170 --> 00:04:59,730
But it turns out
this is not quite true.

107
00:04:59,730 --> 00:05:01,270

The brain does,
obviously, have

108
00:05:01,270 --> 00:05:03,400
some very important roles
to play,

109
00:05:03,400 --> 00:05:06,600
but people have been researching
for quite a while

110
00:05:06,600 --> 00:05:09,170
the fact that if you remove
the brain from an animal,

111
00:05:09,170 --> 00:05:12,230
what's called decerebration,

112
00:05:12,230 --> 00:05:14,200
or a decerebrated animal,

113
00:05:14,200 --> 00:05:17,670
where they sever the cerebellum
from the brain stem.

114
00:05:17,670 --> 00:05:19,770
It turns out they can do
all sorts of very interesting

115
00:05:19,770 --> 00:05:21,270
and complicated actions.

116
00:05:21,270 --> 00:05:23,830
All right, everything from--
like, they've put cows

117
00:05:23,830 --> 00:05:25,970
on tilt tables,
this was done a long time ago,

118
00:05:25,970 --> 00:05:27,970
where, you know, it would--
it would resist the--

119
00:05:27,970 --> 00:05:29,900
the changing gravity field.

120
00:05:29,900 --> 00:05:30,970
You can see them walking.

121
00:05:30,970 --> 00:05:32,130
You can see them scratching,

122
00:05:32,130 --> 00:05:33,770
all these very complicated
motions.

123
00:05:33,770 --> 00:05:35,770
And we've all heard about
chickens running around

124
00:05:35,770 --> 00:05:38,800
with their heads cut off,
and--and this is real.

125
00:05:38,800 --> 00:05:40,500
You can do it.
You can go to a farm.

126
00:05:40,500 --> 00:05:42,900
I've done this
and ended up eating a chicken.

127
00:05:42,900 --> 00:05:44,300
[laughter]

128
00:05:44,300 --> 00:05:49,200
And it is notable that
the chicken with no head

129
00:05:49,200 --> 00:05:52,500
is no longer purposeful
in where it's going.

130
00:05:52,500 --> 00:05:54,470
It's running randomly around.
It doesn't have a goal.

131
00:05:54,470 --> 00:05:56,300
It doesn't have a direction,
right?

132
00:05:56,300 --> 00:05:59,200
But it is coordinating
hundreds of muscles

133
00:05:59,200 --> 00:06:01,570
and managing its balance
on two legs,

134
00:06:01,570 --> 00:06:04,230
and that's a very complex set
of behaviors to do.

135
00:06:04,230 --> 00:06:06,500
And the brain is
mechanically removed,

136
00:06:06,500 --> 00:06:08,130
so you know that's not
part of the solution.

137
00:06:08,130 --> 00:06:11,670
So this has been more formally
studied, as I mentioned.

138
00:06:11,670 --> 00:06:13,530
I'm gonna show you a video
that was made

139
00:06:13,530 --> 00:06:16,570
almost a century ago by one of
the earliest researchers

140
00:06:16,570 --> 00:06:19,800
into this field who showed that
locomotion can occur

141
00:06:19,800 --> 00:06:22,970
purely in the spine,
from processes in the spine.

142
00:06:22,970 --> 00:06:24,600
Now, this is a video of a cat,

143
00:06:24,600 --> 00:06:28,330
so anyone who's gonna be
disturbed by that,

144
00:06:28,330 --> 00:06:29,730
it still has its head attached,

145
00:06:29,730 --> 00:06:32,330
but as I said,
the brain has been removed.

146
00:06:32,330 --> 00:06:34,370
You know, you can feel free
to cover your eyes.

147
00:06:34,370 --> 00:06:36,770
But I always figure that since
the science has been done,

148
00:06:36,770 --> 00:06:38,130
we might as well learn from it.

149
00:06:38,130 --> 00:06:40,100

So hang with it if you can.

150
00:06:40,100 --> 00:06:43,470
So what you see in this video
is that the cat,

151
00:06:43,470 --> 00:06:46,000
as the treadmill goes through
different speeds,

152
00:06:46,000 --> 00:06:48,730
the cat will express three
different types of gaits.

153
00:06:48,730 --> 00:06:51,300
It will go from a walk
to a trot to a gallop.

154
00:06:51,300 --> 00:06:53,300
And we know, again, as I said,

155
00:06:53,300 --> 00:06:55,000
that the brain
is not involved in this.

156
00:06:55,000 --> 00:06:56,530
This is purely from the spine,

157
00:06:56,530 --> 00:06:59,300
and the spine is interesting.
It's decentralized.

158
00:06:59,300 --> 00:07:03,600
It has each vertebra is its own
little node of neurons,

159
00:07:03,600 --> 00:07:06,030
and so it's this segmented,

160

00:07:06,030 --> 00:07:08,870
modular, decentralized system.

161
00:07:08,870 --> 00:07:10,570
So there's not some central CPU.

162
00:07:10,570 --> 00:07:13,330
There's not some motor cortex
in the middle of the spine

163
00:07:13,330 --> 00:07:14,800
that's coordinating all of this.

164
00:07:14,800 --> 00:07:16,630
So you're getting
this coordination

165
00:07:16,630 --> 00:07:17,900
out of a decentralized system,

166
00:07:17,900 --> 00:07:19,530
and that's a very,
very important clue.

167
00:07:19,530 --> 00:07:23,730
And we're gonna come back to it
a lot later on in the talk.

168
00:07:23,730 --> 00:07:27,230
So that's my teaser for the--

169
00:07:27,230 --> 00:07:30,170
for the controls
and to get you out of

170
00:07:30,170 --> 00:07:32,030
maybe your comfort zone
of thinking of how the brain

171

00:07:32,030 --> 00:07:34,030
might be at the center
of everything.

172
00:07:34,030 --> 00:07:35,630
We will get back to it
at the end of the talk,

173
00:07:35,630 --> 00:07:39,000
but to really dive into
understanding all this,

174
00:07:39,000 --> 00:07:40,200
we also have to look at the body

175
00:07:40,200 --> 00:07:41,670
and understand how it functions,
all right.

176
00:07:41,670 --> 00:07:43,730
No matter how smart
your control system is

177
00:07:43,730 --> 00:07:45,530
you can't make a brick fly,
all right.

178
00:07:45,530 --> 00:07:47,600
You have to combine
both the structure

179
00:07:47,600 --> 00:07:50,300
and the controls together
in an intelligent way.

180
00:07:50,300 --> 00:07:54,130
So you may have had
this skeleton

181
00:07:54,130 --> 00:07:58,070

in your classroom, biology
classroom in elementary school.

182
00:07:58,070 --> 00:07:59,730
There are very useful
initial insights to it

183
00:07:59,730 --> 00:08:01,930
but it's telling you a lie,
all right.

184
00:08:01,930 --> 00:08:04,900
You look at this
and it leads you to think

185
00:08:04,900 --> 00:08:07,670
that the skeleton is this thing,
this, like, structure

186
00:08:07,670 --> 00:08:09,570
kind of like the rafters

187
00:08:09,570 --> 00:08:11,570
and, you know, the
infrastructure of a house,

188
00:08:11,570 --> 00:08:13,000
the--the, you know,
the walls and the roof

189
00:08:13,000 --> 00:08:15,170
and the ceiling joists
and all that.

190
00:08:15,170 --> 00:08:17,430
But actually, it's held together
by a bunch of aftermarket pins

191
00:08:17,430 --> 00:08:19,930
and hinges that don't exist

in reality.

192
00:08:19,930 --> 00:08:21,500
If it was really just
a bunch of bones,

193
00:08:21,500 --> 00:08:23,600
it would be a pile of bones
on the floor, right.

194
00:08:23,600 --> 00:08:25,430
What holds our body together

195
00:08:25,430 --> 00:08:27,400
is all this soft
tensile material,

196
00:08:27,400 --> 00:08:30,770
the muscles, the ligaments,
the tendons, all right,

197
00:08:30,770 --> 00:08:33,430
collectively often called
the fascia.

198
00:08:33,430 --> 00:08:37,330
And--and what you'll see here
on this MRI video

199
00:08:37,330 --> 00:08:39,930
on the side
is that the bones

200
00:08:39,930 --> 00:08:43,030
don't just move around
a single axis hinge

201
00:08:43,030 --> 00:08:44,370
like is often assumed.

202
00:08:44,370 --> 00:08:46,070
If you think like, oh, my knee,
it's a hinge, right?

203
00:08:46,070 --> 00:08:47,600
I can just bend it.

204
00:08:47,600 --> 00:08:50,200
Actually what you see is the
bones do very complex gliding

205
00:08:50,200 --> 00:08:53,400
and sliding motion because
they're not just pin hinged.

206
00:08:53,400 --> 00:08:55,270
There's no pin
holding it together.

207
00:08:55,270 --> 00:08:57,330
It's the soft material that
holds it all together

208
00:08:57,330 --> 00:09:00,570
and allows for very complex
multidimensional motions

209
00:09:00,570 --> 00:09:02,430
of the bones relative
to each other.

210
00:09:02,430 --> 00:09:04,170
And that turns out to be
very important.

211
00:09:04,170 --> 00:09:06,900
It looks like, from the outside,
a very subtle difference.

212

00:09:06,900 --> 00:09:09,070
Very easy to say,
okay, this is just a hinge.

213
00:09:09,070 --> 00:09:10,770
But if you actually start
looking at how forces

214
00:09:10,770 --> 00:09:14,170
flow through the structure
and what becomes possible

215
00:09:14,170 --> 00:09:16,870
when you have
all this complexity

216
00:09:16,870 --> 00:09:18,930
and freedom of motion
between the bones,

217
00:09:18,930 --> 00:09:21,100
it opens up a whole different
design space

218
00:09:21,100 --> 00:09:26,030
than we are accustomed to using
in traditional robots.

219
00:09:26,030 --> 00:09:28,070
So as I mentioned,
this soft tissue...

220
00:09:28,070 --> 00:09:29,500
We're gonna dive into it more.

221
00:09:29,500 --> 00:09:32,200
is often, again, sort of
collectively known as fascia,

222
00:09:32,200 --> 00:09:34,030

the connective tissue.

223
00:09:34,030 --> 00:09:36,500
It was often ignored early on in
anatomical studies, right?

224
00:09:36,500 --> 00:09:38,700
People looked at, oh, it's
the muscles. It's the bones.

225
00:09:38,700 --> 00:09:40,770
These are the, you know,
simple segments

226
00:09:40,770 --> 00:09:42,270
and we cut all
the other stuff apart.

227
00:09:42,270 --> 00:09:43,570
The tendons are just connectors

228
00:09:43,570 --> 00:09:46,330
between the motors
and the bones.

229
00:09:46,330 --> 00:09:47,730
Well, it turns out that
the fascia is actually

230
00:09:47,730 --> 00:09:49,130
a continuous system.

231
00:09:49,130 --> 00:09:50,270
Unlike the bones
which will just end up

232
00:09:50,270 --> 00:09:51,930
being a pile on the floor,

233

00:09:51,930 --> 00:09:54,630
it's the fascia that is
continuous from end to end.

234
00:09:54,630 --> 00:09:57,730
It is the outer layer
of your bones,

235
00:09:57,730 --> 00:10:00,100
the periosteum,
is a bunch of fibers

236
00:10:00,100 --> 00:10:03,300
and those fibers are continuous
with the fibers of your tendon.

237
00:10:03,300 --> 00:10:06,400
And those fibers are continuous
with your--

238
00:10:06,400 --> 00:10:08,570
the fibers that are all through
and around your muscles.

239
00:10:08,570 --> 00:10:12,500
And in fact, when you start off
as embryonic,

240
00:10:12,500 --> 00:10:14,800
you start off
as a mass of fascia,

241
00:10:14,800 --> 00:10:16,500
as a mass of soft tissue.

242
00:10:16,500 --> 00:10:18,930
And it's only later
during your development

243
00:10:18,930 --> 00:10:21,600

that the bones start to
harden into the pockets.

244
00:10:21,600 --> 00:10:25,270
Muscles and bones grow into
the pockets in the soft tissue.

245
00:10:25,270 --> 00:10:28,730
So this soft tissue is the
fundamental form of your body,

246
00:10:28,730 --> 00:10:31,030
and bones and muscles
come later.

247
00:10:31,030 --> 00:10:32,630
Very important.

248
00:10:32,630 --> 00:10:35,100
So people have been
studying this

249
00:10:35,100 --> 00:10:38,500
There is--Tom Myers
is one of the researchers

250
00:10:38,500 --> 00:10:41,530
and--who's looked a lot
into mapping

251
00:10:41,530 --> 00:10:46,000
the long-distance chains
of soft tissue in the body

252
00:10:46,000 --> 00:10:47,830
and he's worked with
a bunch of other anatomists,

253
00:10:47,830 --> 00:10:51,730
sort of a new revolutionary way

of doing dissections in anatomy.

254
00:10:51,730 --> 00:10:55,400
And they work with unpreserved,
fresh cadavers,

255
00:10:55,400 --> 00:10:56,870
because when you take
formaldehyde

256
00:10:56,870 --> 00:10:58,530
and you preserve a cadaver,

257
00:10:58,530 --> 00:11:01,030
it binds and hardens
all the fascia together,

258
00:11:01,030 --> 00:11:02,930
and it loses some of
the key qualities that matter

259
00:11:02,930 --> 00:11:04,970
in a living body, all right.

260
00:11:04,970 --> 00:11:06,500
So they've been doing
these dissections

261
00:11:06,500 --> 00:11:09,430
and trying to follow the long
lines of fibers in the body,

262
00:11:09,430 --> 00:11:11,270
and what you see over here,
for instance,

263
00:11:11,270 --> 00:11:13,800
is the continuous connection

264

00:11:13,800 --> 00:11:17,170
from the trapezius,
sort of the muscles up here,

265
00:11:17,170 --> 00:11:18,570
all the way down
to your fingers.

266
00:11:18,570 --> 00:11:20,930
That is one system,
and it's actually continuous

267
00:11:20,930 --> 00:11:22,600
with the rest of the body, too,
right.

268
00:11:22,600 --> 00:11:24,830
But that's just one segment
that you can go look at.

269
00:11:24,830 --> 00:11:27,030
And so now
you start thinking about

270
00:11:27,030 --> 00:11:29,870
the tensile connections

271
00:11:29,870 --> 00:11:32,900
and pathways in the body
as being the primary way

272
00:11:32,900 --> 00:11:35,900
that forces and loads are
transmitted through the body,

273
00:11:35,900 --> 00:11:37,100
and those are important, right?

274
00:11:37,100 --> 00:11:38,700
When you move, you step,

when you push on things,

275
00:11:38,700 --> 00:11:40,930
those are all forces and loads
that you need to move through

276
00:11:40,930 --> 00:11:42,800
the body in different ways

277
00:11:42,800 --> 00:11:45,170
and control and manage in order
to be able to walk and move

278
00:11:45,170 --> 00:11:47,170
and carry things of the world.

279
00:11:47,170 --> 00:11:49,270
So what's really interesting,
and this is--

280
00:11:49,270 --> 00:11:51,400
this becomes much more
speculative is that Tom Myers,

281
00:11:51,400 --> 00:11:54,170
he calls one of his books
"Anatomy Trains,"

282
00:11:54,170 --> 00:11:57,470
he's mapped out a number of
these long-distance pathways

283
00:11:57,470 --> 00:11:59,370
and he finds that they end up
looking a lot like

284
00:11:59,370 --> 00:12:02,070
the meridians of Chinese
acupuncture, right,

285
00:12:02,070 --> 00:12:04,430
and so that's interesting.

286
00:12:04,430 --> 00:12:06,770
There's some research
that sort of indicates

287
00:12:06,770 --> 00:12:10,400
that, again, it's along these
pathways of tensile load-bearing

288
00:12:10,400 --> 00:12:13,500
that you get your primary
proprioceptive centers.

289
00:12:13,500 --> 00:12:15,830
All the strain gauges,
the Golgi tendon organs

290
00:12:15,830 --> 00:12:18,430
is what they're called,
and other sensors

291
00:12:18,430 --> 00:12:20,430
that tell us where
and how our body is moving

292
00:12:20,430 --> 00:12:21,900
and dealing with forces,

293
00:12:21,900 --> 00:12:25,630
tend to concentrate along these
pathways of load transfer,

294
00:12:25,630 --> 00:12:26,770
which makes sense.

295
00:12:26,770 --> 00:12:28,200
That's right where

the loads are,

296
00:12:28,200 --> 00:12:29,670
that's right where we need
to measure things.

297
00:12:29,670 --> 00:12:30,870
And so it is possible that

298
00:12:30,870 --> 00:12:32,570
that's part of what
acupuncture is doing

299
00:12:32,570 --> 00:12:35,430
is starting to play with these
sensory inputs to ourselves,

300
00:12:35,430 --> 00:12:38,500
and therefore, jiggle with
our control systems

301
00:12:38,500 --> 00:12:40,700
in interesting and unique ways.

302
00:12:40,700 --> 00:12:42,530
Very speculative at that point.

303
00:12:42,530 --> 00:12:44,630
So...

304
00:12:44,630 --> 00:12:46,830
Now, having sort of introduced
this idea of the body

305
00:12:46,830 --> 00:12:49,000
as primarily a tensile system,

306
00:12:49,000 --> 00:12:50,900
though it obviously does have

bones in there.

307
00:12:50,900 --> 00:12:52,200
They are playing a role.

308
00:12:52,200 --> 00:12:53,270
I wanted to sort of point out,

309
00:12:53,270 --> 00:12:54,570
like, what are we used to
building?

310
00:12:54,570 --> 00:12:56,170
We're used to building things
like this,

311
00:12:56,170 --> 00:12:59,130
like this house on the side of
the picture here, this building.

312
00:12:59,130 --> 00:13:01,100
We build static objects
that are load-bearing.

313
00:13:01,100 --> 00:13:03,600
We call them continuous
compression structures, right.

314
00:13:03,600 --> 00:13:06,430
The load of the roof rests on
the walls

315
00:13:06,430 --> 00:13:08,170
and that passes
to the next floor down,

316
00:13:08,170 --> 00:13:09,730
and it accumulates
and accumulates load

317
00:13:09,730 --> 00:13:11,600
all the way down to the ground.

318
00:13:11,600 --> 00:13:13,970
I used to work with this robot

319
00:13:13,970 --> 00:13:17,770
that--that was built down at
JPL, Jet Propulsion Laboratory,

320
00:13:17,770 --> 00:13:19,930
and it's called ATHLETE.

321
00:13:19,930 --> 00:13:21,600
It was designed to carry

322
00:13:21,600 --> 00:13:23,900
lunar habitat infrastructure
components,

323
00:13:23,900 --> 00:13:27,500
big pieces of--
of hardware on the moon,

324
00:13:27,500 --> 00:13:29,470
where you don't have forklifts
to take it off the lander

325
00:13:29,470 --> 00:13:31,000
and all of that.

326
00:13:31,000 --> 00:13:33,400
So it was able to walk and roll,
do all sorts of amazing things.

327
00:13:33,400 --> 00:13:37,000
It has six legs with seven
degrees of freedom in each leg.

328
00:13:37,000 --> 00:13:39,470
And the most recent version of
ATHLETE

329
00:13:39,470 --> 00:13:40,830
was, I think, six meters.

330
00:13:40,830 --> 00:13:43,130
It could spread its legs
up to six meters wide, four--

331
00:13:43,130 --> 00:13:45,570
It could stand four meters tall,
very big robot.

332
00:13:45,570 --> 00:13:48,300
And I was working on
walking algorithms for it.

333
00:13:48,300 --> 00:13:50,530
And this robot can do
amazing things, right.

334
00:13:50,530 --> 00:13:52,800
It can climb over complex cliffs
and ledges.

335
00:13:52,800 --> 00:13:55,430
Takes all day to sort of figure
out every little detail

336
00:13:55,430 --> 00:13:57,070
to make it happen,
but it can do it, right?

337
00:13:57,070 --> 00:13:58,830
Really capable robot.

338
00:13:58,830 --> 00:14:02,030

And yet, there we were sometimes
in the Mars Yard,

339
00:14:02,030 --> 00:14:04,430
which is their flat dirt yard
where they do Rover testing,

340
00:14:04,430 --> 00:14:06,400
and would be on what to the rest
of us would appear

341
00:14:06,400 --> 00:14:10,630
essentially flat ground, and--
dirt ground,

342
00:14:10,630 --> 00:14:13,530
and suddenly one of the ankles
would be completely saturated,

343
00:14:13,530 --> 00:14:15,800
like, over-torqued,
couldn't do anything.

344
00:14:15,800 --> 00:14:17,330
We had to sort of reposition
the whole robot

345
00:14:17,330 --> 00:14:19,100
until we got the loads
off of that ankle

346
00:14:19,100 --> 00:14:21,370
and it could move again
on flat ground.

347
00:14:21,370 --> 00:14:24,200
And what I came to realize
was that

348
00:14:24,200 --> 00:14:26,170

because it's
a rigid structure--

349
00:14:26,170 --> 00:14:28,170
there's this rigid pinned
connection

350
00:14:28,170 --> 00:14:29,470
between all the components--

351
00:14:29,470 --> 00:14:32,570
you were able to get
six-meter-long lever arms

352
00:14:32,570 --> 00:14:34,230
internal to the structure.

353
00:14:34,230 --> 00:14:37,000
So even if you stood on some
small, little lump of dirt,

354
00:14:37,000 --> 00:14:39,170
that could be enough,
with a six-meter--

355
00:14:39,170 --> 00:14:41,200
six meters of leverage

356
00:14:41,200 --> 00:14:44,970
to cause enormous torques and
loads to enter into the joints.

357
00:14:44,970 --> 00:14:47,270
And this is one of
the core limitations

358
00:14:47,270 --> 00:14:50,830
of sort of a traditional,
rigidly defined structure.

359
00:14:50,830 --> 00:14:52,470
And if you really want
to think about it in a--

360
00:14:52,470 --> 00:14:55,630
in a more sort of
philosophical perspective,

361
00:14:55,630 --> 00:14:57,930
these kinds of rigidly designed
systems

362
00:14:57,930 --> 00:14:59,900
where everything is sort of
connected together

363
00:14:59,900 --> 00:15:01,300
the way we build our houses,

364
00:15:01,300 --> 00:15:03,570
they're really good for
building static structures,

365
00:15:03,570 --> 00:15:04,730
something that's gonna
sit still.

366
00:15:04,730 --> 00:15:05,970
You define all the load paths.

367
00:15:05,970 --> 00:15:07,100
You know exactly where
it's gonna go.

368
00:15:07,100 --> 00:15:08,770
You put the materials
exactly there.

369
00:15:08,770 --> 00:15:11,070

It supports the loads,
boom, you're fine.

370
00:15:11,070 --> 00:15:12,500
And then we've taken that
concept

371
00:15:12,500 --> 00:15:14,470
and we started adding motors to
it and said, hey, look,

372
00:15:14,470 --> 00:15:15,700
we can make moving structures.

373
00:15:15,700 --> 00:15:17,900
But it's the wrong
structural concept

374
00:15:17,900 --> 00:15:20,930
for something that's
intended to move.

375
00:15:20,930 --> 00:15:24,270
So this is what brings us to
tensegrity structures.

376
00:15:24,270 --> 00:15:28,270
Tensegrity is a word coined by
Buckminster Fuller.

377
00:15:28,270 --> 00:15:30,930
It comes from "tension"
and "integrity."

378
00:15:30,930 --> 00:15:33,170
And it is this structural
concept

379
00:15:33,170 --> 00:15:35,070
that looks at

the tensile network

380
00:15:35,070 --> 00:15:37,470
as the primary system

381
00:15:37,470 --> 00:15:39,930
for integrating the whole
structure, right.

382
00:15:39,930 --> 00:15:43,270
So you get these very
interesting art structures

383
00:15:43,270 --> 00:15:45,670
where these rods are just
floating in space

384
00:15:45,670 --> 00:15:47,930
and they're held together by
the tension network of cables.

385
00:15:47,930 --> 00:15:51,000
Very fascinating,
very sort of awe-inspiring.

386
00:15:51,000 --> 00:15:53,730
You can--if you're local,
you can go to Stanford

387
00:15:53,730 --> 00:15:55,800
and there's one of them
on the campus there.

388
00:15:55,800 --> 00:15:59,370
So I think maybe my years there
made it sort of intuitive to me

389
00:15:59,370 --> 00:16:02,970
that such a thing would exist
and--and it was sensible.

390
00:16:02,970 --> 00:16:05,330
But it's very counter to
our traditional way of thinking

391
00:16:05,330 --> 00:16:07,430
about structures.

392
00:16:07,430 --> 00:16:11,500
They have a number of really
interesting physical properties,

393
00:16:11,500 --> 00:16:14,200
now that you've sort of switched
around how things work.

394
00:16:14,200 --> 00:16:16,570
One of them is that
they have a very high

395
00:16:16,570 --> 00:16:18,400
strength-to-weight ratio, right.

396
00:16:18,400 --> 00:16:21,000
The--the--the materials are
either experiencing

397
00:16:21,000 --> 00:16:22,730
pure compression,

398
00:16:22,730 --> 00:16:25,000
where those rods are being
squeezed by the tensile network,

399
00:16:25,000 --> 00:16:27,500
or the cables are experiencing
pure tension.

400
00:16:27,500 --> 00:16:31,130

So you don't need to deal with
bending and shear forces

401
00:16:31,130 --> 00:16:33,870
to the same extent you do
in a traditional mechanism.

402
00:16:33,870 --> 00:16:36,370
You're also--you don't have
internal lever arms

403
00:16:36,370 --> 00:16:39,300
where you are magnifying
the forces into joints,

404
00:16:39,300 --> 00:16:42,170
like I showed on that JPL robot,
the ATHLETE,

405
00:16:42,170 --> 00:16:44,570
which is a great robot,
by the way.

406
00:16:44,570 --> 00:16:47,130
You're not magnifying those
forces into those joints

407
00:16:47,130 --> 00:16:50,000
so you don't have to massively
oversize them to,

408
00:16:50,000 --> 00:16:52,600
you know, deal with all
the forces that accumulate.

409
00:16:52,600 --> 00:16:55,400
Instead, these structures have
an interesting property

410
00:16:55,400 --> 00:16:58,530

of distributing and diffusing
applied loads.

411
00:16:58,530 --> 00:16:59,970
You see on my little chart here,

412
00:16:59,970 --> 00:17:02,800
if you push down
on one of those rods,

413
00:17:02,800 --> 00:17:05,770
that force actually propagates
and diffuses

414
00:17:05,770 --> 00:17:07,770
through the whole structure
such that all the cables

415
00:17:07,770 --> 00:17:11,200
and all the rods participate
in absorbing that stress

416
00:17:11,200 --> 00:17:12,900
and it spreads it out.

417
00:17:12,900 --> 00:17:14,730
And this is something that you
see in our bodies, too, right.

418
00:17:14,730 --> 00:17:16,500
We do amazing things

419
00:17:16,500 --> 00:17:18,370
because we are able to use
our whole bodies

420
00:17:18,370 --> 00:17:20,930
to, you know, hold ourselves in
strange and--

421
00:17:20,930 --> 00:17:22,830
and awkward positions.

422
00:17:22,830 --> 00:17:25,470
I'll show you some images
of that later.

423
00:17:25,470 --> 00:17:28,500
And another thing that's very
valuable about these

424
00:17:28,500 --> 00:17:30,570
is that they have
tunable stiffness.

425
00:17:30,570 --> 00:17:34,270
You find this in modern robotics
as we take robots out of the lab

426
00:17:34,270 --> 00:17:36,800
and we try to get them to move
in real-world situations,

427
00:17:36,800 --> 00:17:38,730
how stiff you are
is very important, right.

428
00:17:38,730 --> 00:17:40,700
If you bump into something
accidentally,

429
00:17:40,700 --> 00:17:42,030
you want to be soft.

430
00:17:42,030 --> 00:17:45,430
You want to not break the podium
or yourself, right.

431
00:17:45,430 --> 00:17:47,030

You want to comply to that.

432
00:17:47,030 --> 00:17:49,400
Yet, at the same time, if you
want to pick up a heavy load,

433
00:17:49,400 --> 00:17:51,200
you need to become a little
rigid to do that.

434
00:17:51,200 --> 00:17:52,770
Otherwise you're just
gonna be floppy.

435
00:17:52,770 --> 00:17:54,130
You're not gonna be able
to get anything done, right.

436
00:17:54,130 --> 00:17:55,900
So you need to be able to change
your stiffness

437
00:17:55,900 --> 00:17:57,470
in order to do different things.

438
00:17:57,470 --> 00:17:59,830
As you move across different
soils, different terrains,

439
00:17:59,830 --> 00:18:01,300
you need to change
your stiffness

440
00:18:01,300 --> 00:18:02,900
to adapt to the type of terrain
you're on.

441
00:18:02,900 --> 00:18:04,770
If you're on hard soil
versus sand,

442
00:18:04,770 --> 00:18:06,430
you actually want a different
stiffness in your body

443
00:18:06,430 --> 00:18:09,730
so that you can move
efficiently.

444
00:18:09,730 --> 00:18:11,370
And these structures enable that

445
00:18:11,370 --> 00:18:13,070
because they are pre-tensioned.

446
00:18:13,070 --> 00:18:14,900
You can change all the--
tighten up all the cables

447
00:18:14,900 --> 00:18:16,470
and the whole thing
becomes stiffer.

448
00:18:16,470 --> 00:18:18,370
What's interesting about it,
though,

449
00:18:18,370 --> 00:18:21,170
is that these structures are
hard to make static.

450
00:18:21,170 --> 00:18:23,270
If you look at those art
structures that I showed you

451
00:18:23,270 --> 00:18:26,070
on the last slide,
they're--you know,

452

00:18:26,070 --> 00:18:27,870
people have talked about this
in architecture.

453
00:18:27,870 --> 00:18:29,500
They're like, oh, we can make
buildings out of this.

454
00:18:29,500 --> 00:18:31,700
We're like, well, they're not
great at static structures.

455
00:18:31,700 --> 00:18:33,430
They always want to oscillate.

456
00:18:33,430 --> 00:18:35,100
They always want to move
a little bit,

457
00:18:35,100 --> 00:18:36,900
and we'll come back to this when
we get to the control section,

458
00:18:36,900 --> 00:18:38,830
but it's an important quality.

459
00:18:38,830 --> 00:18:41,030
These are structures
that want to move.

460
00:18:41,030 --> 00:18:44,270
Inherently the quality
of the system.

461
00:18:44,270 --> 00:18:47,130
So that seems to make sense as
something you'd want to do

462
00:18:47,130 --> 00:18:50,000
if you were gonna build a robot

that moves.

463
00:18:50,000 --> 00:18:51,730
Other interesting clues we have

464
00:18:51,730 --> 00:18:53,230
is that there are
a number of researchers

465
00:18:53,230 --> 00:18:55,970
who have been looking at
tensegrity systems in biology.

466
00:18:55,970 --> 00:18:58,130
So we have folks like
Donald Ingber

467
00:18:58,130 --> 00:18:59,730
at the Harvard Wyss Institute

468
00:18:59,730 --> 00:19:01,670
who has spent
the last 20, 30 years

469
00:19:01,670 --> 00:19:03,970
looking at cell structures,

470
00:19:03,970 --> 00:19:06,500
the microtubules
and microfilaments in cells,

471
00:19:06,500 --> 00:19:09,470
and seeing a lot of similarity
to the tensegrity systems

472
00:19:09,470 --> 00:19:11,430
that we build as--as humans.

473
00:19:11,430 --> 00:19:15,070

And so he's built various models
of them.

474
00:19:15,070 --> 00:19:18,430
And there's other folks who are
looking at our gross physiology

475
00:19:18,430 --> 00:19:21,470
as tensegrity structures, right,
so spines and knees and legs.

476
00:19:21,470 --> 00:19:23,400
And a spine's a really
interesting one, right?

477
00:19:23,400 --> 00:19:26,570
I have this model in my lab,
or a similar model to it,

478
00:19:26,570 --> 00:19:27,770
and you can compress it.

479
00:19:27,770 --> 00:19:29,470
You can put load on it

480
00:19:29,470 --> 00:19:31,130
and the vertebrae don't touch.

481
00:19:31,130 --> 00:19:33,230
All the forces pass through
the cables, right.

482
00:19:33,230 --> 00:19:34,870
And it can still hold itself up

483
00:19:34,870 --> 00:19:36,630
and all the vertebrae
are kind of floating,

484

00:19:36,630 --> 00:19:38,200
and this is really compelling,
right.

485
00:19:38,200 --> 00:19:40,800
It's--it's not an exact model of
how our spine works.

486
00:19:40,800 --> 00:19:42,430
It's abstracted and simplified,

487
00:19:42,430 --> 00:19:44,400
and there's a lot of research
still to be done here,

488
00:19:44,400 --> 00:19:47,300
but, you know, we--
what one would wonder,

489
00:19:47,300 --> 00:19:49,730
if you take the traditional view
of our spine

490
00:19:49,730 --> 00:19:51,570
being a stack of vertebrae
and disks,

491
00:19:51,570 --> 00:19:52,970
why don't we all have
bulging disks?

492
00:19:52,970 --> 00:19:55,000
Why don't we all have
pinched nerves, right?

493
00:19:55,000 --> 00:19:56,430
One of the arguments that I make

494
00:19:56,430 --> 00:20:00,330
is that because primarily

495
00:20:00,330 --> 00:20:03,870
the loads and forces should be
passing through your muscles

496
00:20:03,870 --> 00:20:06,330
and your tendons and ligaments,

497
00:20:06,330 --> 00:20:08,800
and it's when you get
out of balance,

498
00:20:08,800 --> 00:20:11,500
when you've been spending
ten hours a day sitting,

499
00:20:11,500 --> 00:20:13,700
working or in front of
the television or in a car,

500
00:20:13,700 --> 00:20:16,970
that you are starting to get
a dysfunction

501
00:20:16,970 --> 00:20:18,500
in that balance of tension

502
00:20:18,500 --> 00:20:21,730
and no longer keep those
vertebrae floating separately

503
00:20:21,730 --> 00:20:23,000
like they should be.

504
00:20:23,000 --> 00:20:26,300
So this--and this story goes
a lot deeper,

505
00:20:26,300 --> 00:20:28,100

but that's just to give
some ideas

506
00:20:28,100 --> 00:20:31,370
of what--what's out there
and what's possible.

507
00:20:31,370 --> 00:20:34,100
So taking all that inspiration,

508
00:20:34,100 --> 00:20:36,430
I'm gonna show you a little bit
of the robotics work

509
00:20:36,430 --> 00:20:39,070
that then we're doing here
at NASA with this

510
00:20:39,070 --> 00:20:41,230
to explore this possibility

511
00:20:41,230 --> 00:20:43,730
as a way to design
the future robots.

512
00:20:43,730 --> 00:20:47,600
And then we'll end up talking
about how we can control them.

513
00:20:47,600 --> 00:20:51,900
So again, SUPERball,
right now we build robots

514
00:20:51,900 --> 00:20:55,170
and then we pack 'em in these--
with various landing systems,

515
00:20:55,170 --> 00:20:58,730
air bags, you know,
sky cranes, whatever,

516
00:20:58,730 --> 00:21:01,500
very complex systems that you
use once and then discard.

517
00:21:01,500 --> 00:21:03,270
It's a lot of mass
that you've wasted.

518
00:21:03,270 --> 00:21:05,430
I mean, you need it 'cause
that's the critical moment,

519
00:21:05,430 --> 00:21:07,900
but could you
get away from that?

520
00:21:07,900 --> 00:21:09,270
And so what
we're showing here is,

521
00:21:09,270 --> 00:21:11,670
in this very first prototype,

522
00:21:11,670 --> 00:21:14,100
we actually designed this
prototype to really explore

523
00:21:14,100 --> 00:21:16,230
how it can move,
how it can roll,

524
00:21:16,230 --> 00:21:18,430
so we put a lot of focus into
its--its--

525
00:21:18,430 --> 00:21:21,330
just the mechatronics of
designing the motors

526
00:21:21,330 --> 00:21:24,200
and actuators and controls
for it

527
00:21:24,200 --> 00:21:26,230
and yet, despite that,
not really--

528
00:21:26,230 --> 00:21:28,330
despite not really focusing on
the landing part,

529
00:21:28,330 --> 00:21:30,730
we were able to, as you see,
drop it off of

530
00:21:30,730 --> 00:21:32,700
even just one-meter-tall
loading docks,

531
00:21:32,700 --> 00:21:36,730
which most robots of this size
don't handle very gracefully.

532
00:21:36,730 --> 00:21:40,370
So that's kind of
where we are.

533
00:21:40,370 --> 00:21:43,170
And what's interesting is when
you build the kind of robot

534
00:21:43,170 --> 00:21:46,100
that--something that could land
from orbit safely

535
00:21:46,100 --> 00:21:47,370
and not break,

536

00:21:47,370 --> 00:21:50,230
it also changes how you explore
another planet.

537
00:21:50,230 --> 00:21:52,130
There's lots of places
we want to go where

538
00:21:52,130 --> 00:21:55,270
the science is not necessarily
the easy place, right?

539
00:21:55,270 --> 00:21:57,270
I mean, nice big, flat fields,
you find a rock,

540
00:21:57,270 --> 00:21:58,630
that's great, right?

541
00:21:58,630 --> 00:22:00,270
We can do that with our Rovers
today.

542
00:22:00,270 --> 00:22:02,570
But science isn't waiting for us

543
00:22:02,570 --> 00:22:03,800
where it's easy for us to go.

544
00:22:03,800 --> 00:22:05,500
We need to build the robots
that can handle

545
00:22:05,500 --> 00:22:07,570
the risky and dangerous places
where the science--

546
00:22:07,570 --> 00:22:09,400
the good science really is.

547
00:22:09,400 --> 00:22:11,600
And so for instance, we want to
explore places like Europa,

548
00:22:11,600 --> 00:22:13,600
one of the icy moons

549
00:22:13,600 --> 00:22:15,800
that may harbor life
under that crust of ice

550
00:22:15,800 --> 00:22:17,530
in that subsurface ocean.

551
00:22:17,530 --> 00:22:20,970
We speculate that the surface
may be very, very jagged

552
00:22:20,970 --> 00:22:24,230
and complicated tumble
of ice blocks

553
00:22:24,230 --> 00:22:26,870
that have, you know, broken
and refused and whatnot.

554
00:22:26,870 --> 00:22:28,500
We don't really know yet,

555
00:22:28,500 --> 00:22:30,130
but it could be a very, very
difficult environment

556
00:22:30,130 --> 00:22:32,730
that a traditional Rover
would not do well with.

557
00:22:32,730 --> 00:22:35,300
So we want to be able to send

a robot there,

558
00:22:35,300 --> 00:22:36,830
or anywhere,

559
00:22:36,830 --> 00:22:39,730
where there's an inherent risk
of it slipping,

560
00:22:39,730 --> 00:22:42,000
an inherent risk of it falling,
right.

561
00:22:42,000 --> 00:22:44,230
That's--that could happen if
you're gonna go somewhere

562
00:22:44,230 --> 00:22:47,070
that's, you know, more complex
than an easy, flat terrain.

563
00:22:47,070 --> 00:22:49,930
And so if that happens, what
robot's gonna survive that?

564
00:22:49,930 --> 00:22:51,830
That's really the quality you
need to--to look at,

565
00:22:51,830 --> 00:22:53,170
the structure of the robot.

566
00:22:53,170 --> 00:22:55,630
How is it gonna survive
the unexpected, right?

567
00:22:55,630 --> 00:22:57,070
You can plan all you want,

568

00:22:57,070 --> 00:22:58,700
but if the soil turns out
from underneath your foot

569
00:22:58,700 --> 00:23:01,100
and you fall,
what happens next?

570
00:23:01,100 --> 00:23:03,830
And so building the robots
that can handle the risk

571
00:23:03,830 --> 00:23:06,970
of real rough--
real-world situations

572
00:23:06,970 --> 00:23:09,470
is sort of one of my motivators
in all of this.

573
00:23:09,470 --> 00:23:13,270
We started doing this a couple
years ago with some funding

574
00:23:13,270 --> 00:23:16,200
from the NASA Innovative
Advanced Concepts Program,

575
00:23:16,200 --> 00:23:19,200
which is a very sort of
early stage new ideas program.

576
00:23:19,200 --> 00:23:21,000
And we started--
I started by building

577
00:23:21,000 --> 00:23:23,370
a physics-based simulator,
NTRT,

578

00:23:23,370 --> 00:23:24,830
the NASA Tensegrity
Robotics Toolkit.

579
00:23:24,830 --> 00:23:26,400
This has actually been
open sourced.

580
00:23:26,400 --> 00:23:28,930
You can find it on GitHub,
and you can use it.

581
00:23:28,930 --> 00:23:30,600
You can--can, you know,

582
00:23:30,600 --> 00:23:32,400
participate in the community
that's using it.

583
00:23:32,400 --> 00:23:35,000
And we have made it easy
to design

584
00:23:35,000 --> 00:23:37,130
new tensegrity structures.

585
00:23:37,130 --> 00:23:40,130
We've integrated all sorts of
machine learning techniques

586
00:23:40,130 --> 00:23:42,530
and some of the neuroscience
inspired control techniques

587
00:23:42,530 --> 00:23:44,630
that I'll mention later,

588
00:23:44,630 --> 00:23:46,670
and really sort of built it up
as a system

589
00:23:46,670 --> 00:23:50,000
that can allow for
the exploration of both form

590
00:23:50,000 --> 00:23:52,630
and structure and locomotion
and movement

591
00:23:52,630 --> 00:23:55,030
and really to try to be a touch
point for a community of people

592
00:23:55,030 --> 00:23:57,900
interested in furthering
this arm of science.

593
00:23:57,900 --> 00:24:00,200
And, of course,
it is an ongoing project,

594
00:24:00,200 --> 00:24:02,530
so it can always use
more help, too.

595
00:24:02,530 --> 00:24:05,570
And so we did various studies,
right.

596
00:24:05,570 --> 00:24:07,430
So this is one study
that just showed

597
00:24:07,430 --> 00:24:08,800
that you can take these--
the structure

598
00:24:08,800 --> 00:24:11,430
and you can pack it flat
and then deploy it,

599
00:24:11,430 --> 00:24:13,030
turn it into its full shape,

600
00:24:13,030 --> 00:24:15,170
and that helps you when you're
launching stuff into space

601
00:24:15,170 --> 00:24:16,700
'cause it all has to fit
into a rocket.

602
00:24:16,700 --> 00:24:19,930
So anything you can pack small
and then deploy is helpful.

603
00:24:19,930 --> 00:24:22,800
You can put a payload
in the center of it

604
00:24:22,800 --> 00:24:25,200
where that ball is
and really protect that.

605
00:24:25,200 --> 00:24:28,100
That ball ends up acting like
the--the key elements

606
00:24:28,100 --> 00:24:29,830
inside your air bag, right.

607
00:24:29,830 --> 00:24:32,130
So you can make sure that,
you know,

608
00:24:32,130 --> 00:24:35,170
your sensitive instruments are
safely protected on landing

609

00:24:35,170 --> 00:24:38,100
It can roll over a variety
of complex terrains.

610
00:24:38,100 --> 00:24:39,870
It is kind of like a ball.

611
00:24:39,870 --> 00:24:41,470
It kind of has that spherical
rolling thing,

612
00:24:41,470 --> 00:24:43,200
but it also has feet,
if you will.

613
00:24:43,200 --> 00:24:45,170
So we call it
punctuated rolling.

614
00:24:45,170 --> 00:24:48,430
It's an interesting hybrid
between rolling and walking.

615
00:24:48,430 --> 00:24:51,100
So there's a lot that it can do.

616
00:24:51,100 --> 00:24:54,970
And then...

617
00:24:54,970 --> 00:24:58,670
It also--I've shown that you
can remove one of the cables

618
00:24:58,670 --> 00:25:00,130
that would normally
have been there,

619
00:25:00,130 --> 00:25:02,270
and you can still get the whole
thing to hold together and roll.

620
00:25:02,270 --> 00:25:04,970
So it's--it's redundant
to some of these failures

621
00:25:04,970 --> 00:25:07,730
that might come up.

622
00:25:07,730 --> 00:25:10,630
And we did some early
prototype testing.

623
00:25:10,630 --> 00:25:13,130
This was with some students
from University of Idaho.

624
00:25:13,130 --> 00:25:14,700
They built various prototypes.

625
00:25:14,700 --> 00:25:17,770
They put--they put
accelerometers in it

626
00:25:17,770 --> 00:25:20,530
and started dropping it
and gathered the data

627
00:25:20,530 --> 00:25:22,570
and found that it matched
our analytical models.

628
00:25:22,570 --> 00:25:23,970
So it really
gave us confidence that

629
00:25:23,970 --> 00:25:26,430
the physics-based simulations
we were doing

630

00:25:26,430 --> 00:25:27,500
were holding up to reality,

631
00:25:27,500 --> 00:25:29,470
in that, okay, this is
reasonable to do

632
00:25:29,470 --> 00:25:31,330
from a structural perspective,

633
00:25:31,330 --> 00:25:34,730
that you could land at
15 meters a second and survive.

634
00:25:34,730 --> 00:25:38,100
So then the next question is,
can you make it move and also--

635
00:25:38,100 --> 00:25:40,000
and have that
whole structure land

636
00:25:40,000 --> 00:25:42,300
at 15 meters a second
and survive?

637
00:25:42,300 --> 00:25:44,300
So we started building
various prototypes

638
00:25:44,300 --> 00:25:46,200
and in that prototype there,
we actually put it

639
00:25:46,200 --> 00:25:48,200
in a motion capture system

640
00:25:48,200 --> 00:25:50,100
and, again, compared it to
our simulator to say,

641
00:25:50,100 --> 00:25:53,100
okay, look, the--the motion
controls that we developed

642
00:25:53,100 --> 00:25:55,530
in simulation seemed to be
holding up in reality.

643
00:25:55,530 --> 00:25:57,130
And then that led us to

644
00:25:57,130 --> 00:25:59,530
the SUPERball prototype
that you see now,

645
00:25:59,530 --> 00:26:01,470
which is our current prototype
that we're working with.

646
00:26:01,470 --> 00:26:03,100
It's not a full prototype.

647
00:26:03,100 --> 00:26:05,170
It's--it's, you know, kind of
got half the actuators

648
00:26:05,170 --> 00:26:06,530
that we'd like it to have,

649
00:26:06,530 --> 00:26:08,700
and there's already many lessons
we've learned

650
00:26:08,700 --> 00:26:11,430
that we're gonna, hopefully, fix
in the next version.

651
00:26:11,430 --> 00:26:12,730

But this is how science goes.

652
00:26:12,730 --> 00:26:14,270
You--you start with
what you can and--

653
00:26:14,270 --> 00:26:16,200
and it gets better over time.

654
00:26:16,200 --> 00:26:19,230
We looked at, you know,
putting payloads in it

655
00:26:19,230 --> 00:26:20,600
and controlling
where the payload is.

656
00:26:20,600 --> 00:26:22,070
So even if you have
an instrument in that payload,

657
00:26:22,070 --> 00:26:24,030
you can drop the payload
down to the ground

658
00:26:24,030 --> 00:26:26,330
and take direct samples
of the soil

659
00:26:26,330 --> 00:26:28,130
is one of the things you can do.

660
00:26:28,130 --> 00:26:31,100
And now that we understand

661
00:26:31,100 --> 00:26:34,930
how to do a lot of
the basics of locomotion

662

00:26:34,930 --> 00:26:36,630
with this robot,

663
00:26:36,630 --> 00:26:39,470
we also are now,

664
00:26:39,470 --> 00:26:41,130
under the Game Changing
Developments Program,

665
00:26:41,130 --> 00:26:42,600
pushing this along.

666
00:26:42,600 --> 00:26:45,030
We're really pushing things
like, how do you control--

667
00:26:45,030 --> 00:26:47,070
how do you understand
where it is in space?

668
00:26:47,070 --> 00:26:48,970
You know, on a traditional
robot, you know--

669
00:26:48,970 --> 00:26:50,470
you can put--you can put
a sensor here

670
00:26:50,470 --> 00:26:52,470
that tells you exactly what
angle the joint is at.

671
00:26:52,470 --> 00:26:55,530
Although, again, this is not
a normal robot joint,

672
00:26:55,530 --> 00:26:58,700
but here we started--it's
a little more complicated.

673
00:26:58,700 --> 00:27:00,570
You've got all this freedom of
motion between the bones,

674
00:27:00,570 --> 00:27:02,530
so how do you tell where they
are relative to each other?

675
00:27:02,530 --> 00:27:05,100
How do you manage to sense
its overall state?

676
00:27:05,100 --> 00:27:08,200
So we--we've pushed
that algorithm forward,

677
00:27:08,200 --> 00:27:12,500
and now we're working with some
collaborators at UC, Berkeley

678
00:27:12,500 --> 00:27:14,970
to use some of their advanced
machine learning techniques

679
00:27:14,970 --> 00:27:17,870
to figure out how to
get this to move, right.

680
00:27:17,870 --> 00:27:19,600
I showed you a lot of stuff
in simulation

681
00:27:19,600 --> 00:27:21,300
and we used
evolutionary algorithms

682
00:27:21,300 --> 00:27:23,130
and--and other sort of machine
learning techniques

683
00:27:23,130 --> 00:27:26,270
that took 10,000 iterations
to--to complete,

684
00:27:26,270 --> 00:27:27,830
which is fine in simulation,

685
00:27:27,830 --> 00:27:29,000
but on a real hardware robot,

686
00:27:29,000 --> 00:27:32,030
you need to do it in
a more efficient manner,

687
00:27:32,030 --> 00:27:34,400
because 10,000 iterations might
become a little tedious

688
00:27:34,400 --> 00:27:36,670
or otherwise threaten
to break your robot.

689
00:27:36,670 --> 00:27:39,530
So what you see here is a really
sort of funny jangly movement.

690
00:27:39,530 --> 00:27:41,470
It's almost like a baby
learning to walk.

691
00:27:41,470 --> 00:27:43,870
It's randomly
moving itself around,

692
00:27:43,870 --> 00:27:47,070
and from doing so, starting to
discover its own dynamics.

693

00:27:47,070 --> 00:27:48,730
And that's part of this
algorithm that

694
00:27:48,730 --> 00:27:50,470
we're working with
from Berkeley,

695
00:27:50,470 --> 00:27:52,070
the Guided Policy Search
algorithm.

696
00:27:52,070 --> 00:27:56,530
It actually helps learn in
a very, very few experiments

697
00:27:56,530 --> 00:27:58,630
on a hardware robot

698
00:27:58,630 --> 00:28:01,100
how to move through
optimal trajectories

699
00:28:01,100 --> 00:28:03,470
and then how to generalize that
to a broader class of--

700
00:28:03,470 --> 00:28:05,830
of motion strategies.

701
00:28:05,830 --> 00:28:07,200
So that's kind of
right where we are

702
00:28:07,200 --> 00:28:08,730
in the control state right now.

703
00:28:08,730 --> 00:28:10,070
We've gotten a little further
than this.

704
00:28:10,070 --> 00:28:12,100
I'm just not showing
the most recent videos.

705
00:28:12,100 --> 00:28:14,600
And then, as I mentioned, we're
making the next prototype,

706
00:28:14,600 --> 00:28:17,330
and we hope to do this over
the course of the next year,

707
00:28:17,330 --> 00:28:19,570
SUPERball 2.0.

708
00:28:19,570 --> 00:28:22,070
Our intention here is to really
now take what we understand

709
00:28:22,070 --> 00:28:24,770
about how to make it move
and make it robust to landing

710
00:28:24,770 --> 00:28:26,400
and we're gonna start
rolling this thing

711
00:28:26,400 --> 00:28:29,170
off the roof of buildings
and have it survive.

712
00:28:29,170 --> 00:28:30,900
That's my hope.

713
00:28:30,900 --> 00:28:33,270
And if that works,
it'll be fun.

714

00:28:33,270 --> 00:28:34,770
And that's just the beginning,
right?

715
00:28:34,770 --> 00:28:36,030
Then we're gonna throw it--

716
00:28:36,030 --> 00:28:37,370
throw it at other planets,
eventually, right, so...

717
00:28:37,370 --> 00:28:39,470
[laughs]
You can't be shy.

718
00:28:39,470 --> 00:28:41,400
[laughter]

719
00:28:41,400 --> 00:28:45,100
One of our other collaborators
is at Rutgers University,

720
00:28:45,100 --> 00:28:46,670
and they've been looking at,

721
00:28:46,670 --> 00:28:48,330
how do you do long-range motion
planning, right?

722
00:28:48,330 --> 00:28:50,800
So you understand the dynamics,
you can get it to roll,

723
00:28:50,800 --> 00:28:53,000
but what if you want to do
really complicated movements

724
00:28:53,000 --> 00:28:54,730
and get through
complex terrains?

725
00:28:54,730 --> 00:28:56,870
And so they've been using
some really advanced

726
00:28:56,870 --> 00:29:00,970
kinodynamic planning algorithms
to look at,

727
00:29:00,970 --> 00:29:05,430
how would you plan a complex
trajectory through there?

728
00:29:05,430 --> 00:29:07,830
So that's sort of
the state of SUPERball.

729
00:29:07,830 --> 00:29:09,900
But SUPERball is really
just the first

730
00:29:09,900 --> 00:29:11,900
of what many possible robots
could be.

731
00:29:11,900 --> 00:29:13,730
Again, this is
a structural concept.

732
00:29:13,730 --> 00:29:16,270
It's a design approach
to robotics,

733
00:29:16,270 --> 00:29:19,600
and so one of the things we look
at when we look back at humans

734
00:29:19,600 --> 00:29:21,600
is that we move from our core,
right.

735
00:29:21,600 --> 00:29:23,900
This is going back to like, how
do people do this stuff, right?

736
00:29:23,900 --> 00:29:25,400
I mean, I can't.
I can do a handstand,

737
00:29:25,400 --> 00:29:27,430
or at least I used to be able
to, but--

738
00:29:27,430 --> 00:29:29,730
[laughs]
but that's crazy.

739
00:29:29,730 --> 00:29:32,570
And you talk to any athlete,
and again, it's from the core,

740
00:29:32,570 --> 00:29:34,970
from the--from your spine
and all these core muscles.

741
00:29:34,970 --> 00:29:36,830
That's the source of motion.

742
00:29:36,830 --> 00:29:39,130
Yet, you know, you ask
an amateur to pick up

743
00:29:39,130 --> 00:29:40,670
a tennis racket and they swing
from their arms, right.

744
00:29:40,670 --> 00:29:43,170
And then the expert learns
to drive from here.

745
00:29:43,170 --> 00:29:46,300
And so you look at our robotics
today, what do we do?

746
00:29:46,300 --> 00:29:49,300
We spend a lot of time, if you
look at legged and armed robots,

747
00:29:49,300 --> 00:29:51,800
we spend a lot of time building
really just complex,

748
00:29:51,800 --> 00:29:54,000
compliant, adaptable
arms and legs

749
00:29:54,000 --> 00:29:55,730
and then bolting it
to a rigid box

750
00:29:55,730 --> 00:29:57,570
and calling it a robot, right.

751
00:29:57,570 --> 00:29:58,630
Great place to start.

752
00:29:58,630 --> 00:30:00,000
We have to start somewhere,

753
00:30:00,000 --> 00:30:02,030
but obviously,
that's still amateur.

754
00:30:02,030 --> 00:30:04,730
All right, if we want to have
really excellent moving robots,

755
00:30:04,730 --> 00:30:07,030
we need to get to the point

where we can understand

756
00:30:07,030 --> 00:30:09,870
how the spine works,
so you can get that dynamic,

757
00:30:09,870 --> 00:30:12,200
flexible, and powerful motion.

758
00:30:12,200 --> 00:30:13,830
Now, the--the challenge is

759
00:30:13,830 --> 00:30:15,730
in a traditional robotics
control approach,

760
00:30:15,730 --> 00:30:17,330
how do you control so many
degrees of freedom,

761
00:30:17,330 --> 00:30:19,330
so many flexible joints
and--and all that?

762
00:30:19,330 --> 00:30:21,000
It's just like--
it breaks all the rules.

763
00:30:21,000 --> 00:30:24,570
It makes the--the algorithms
really, really complicated.

764
00:30:24,570 --> 00:30:27,830
But again, can't be afraid
of--of things that are hard.

765
00:30:27,830 --> 00:30:29,970
Started exploring this,
really looking at

766
00:30:29,970 --> 00:30:31,800
this tensegrity spine model

767
00:30:31,800 --> 00:30:33,230
and exploring,
well, what can we do?

768
00:30:33,230 --> 00:30:35,300
Can we--I want to put arms
and legs on it eventually,

769
00:30:35,300 --> 00:30:36,800
but let's just make it look like
a snake at first

770
00:30:36,800 --> 00:30:37,970
and crawl around just to see,

771
00:30:37,970 --> 00:30:40,530
how do we get those
to control motion?

772
00:30:40,530 --> 00:30:44,370
And it's been a very interesting
path, right?

773
00:30:44,370 --> 00:30:46,570
What we found is that the--

774
00:30:46,570 --> 00:30:49,300
these are very nice, adaptable,
flexible systems.

775
00:30:49,300 --> 00:30:51,330
They respond well
with the integrate forces

776
00:30:51,330 --> 00:30:53,370
from wherever you--

you apply them.

777
00:30:53,370 --> 00:30:55,570
And we started using,

778
00:30:55,570 --> 00:30:58,000
and I'll talk more about this
in our control system,

779
00:30:58,000 --> 00:30:59,970
these ideas out of neuroscience,

780
00:30:59,970 --> 00:31:03,330
central pattern generators,
they are rhythmic controllers.

781
00:31:03,330 --> 00:31:06,930
That--this spine actually has
no central control whatsoever.

782
00:31:06,930 --> 00:31:09,700
Each string has its own
individual controller

783
00:31:09,700 --> 00:31:12,270
and they're all oscillating
in a certain way

784
00:31:12,270 --> 00:31:15,570
such that you get this uniform
behavior of locomotion.

785
00:31:15,570 --> 00:31:17,630
And then we started exploring
around in our simulator

786
00:31:17,630 --> 00:31:19,230
different structures, right.

787

00:31:19,230 --> 00:31:21,770
If you--if you change the design
of the spine

788
00:31:21,770 --> 00:31:23,500
from that first
tetrahedral complex

789
00:31:23,500 --> 00:31:27,730
to these more interesting
sort of vertebrae-like systems

790
00:31:27,730 --> 00:31:29,630
and then throw our machine
learning algorithms

791
00:31:29,630 --> 00:31:32,300
on top of it and explore it
until it kind of defines

792
00:31:32,300 --> 00:31:35,300
an optimal locomotion pattern,
what do you get?

793
00:31:35,300 --> 00:31:37,830
And so it's this--the space

794
00:31:37,830 --> 00:31:40,500
between structural design
and controls

795
00:31:40,500 --> 00:31:42,970
where you can really start
exploring what's possible.

796
00:31:42,970 --> 00:31:45,800
And so then we added ribs to it,
and you know, to sort of--

797
00:31:45,800 --> 00:31:48,170

no direction on how this thing
should learn,

798
00:31:48,170 --> 00:31:49,970
we added ribs
and it started slithering.

799
00:31:49,970 --> 00:31:53,070
I thought that was interesting.

800
00:31:53,070 --> 00:31:54,230
[laughter]

801
00:31:54,230 --> 00:31:55,670
And then, of course, you know,
you can always--

802
00:31:55,670 --> 00:31:57,530
Again, you always have that fear
that--that, you know,

803
00:31:57,530 --> 00:31:58,630
you're doing stuff
in a simulator

804
00:31:58,630 --> 00:32:00,170
and it's just pretty videos.

805
00:32:00,170 --> 00:32:02,130
So we--we built a little
prototype robot

806
00:32:02,130 --> 00:32:04,930
and found that we could use
the same controls

807
00:32:04,930 --> 00:32:07,800
that we were learning at some of
the early tetrahedral ones

808
00:32:07,800 --> 00:32:09,770
and we got very similar motion.

809
00:32:09,770 --> 00:32:13,300
So again, we feel confident
that...

810
00:32:13,300 --> 00:32:17,570
there is some reality
behind those videos

811
00:32:17,570 --> 00:32:20,230
that were built in
the physics simulator.

812
00:32:20,230 --> 00:32:22,070
So spines were a place to start.

813
00:32:22,070 --> 00:32:25,070
And now, working with
some students at UC Santa Cruz,

814
00:32:25,070 --> 00:32:27,370
we were going a little bit more
directly towards what we want,

815
00:32:27,370 --> 00:32:28,870
which is actually
a quadruped robot,

816
00:32:28,870 --> 00:32:30,300
a legged, walking robot.

817
00:32:30,300 --> 00:32:32,330
This is what's gonna really
enable, some day,

818
00:32:32,330 --> 00:32:35,130
the ability to clamber around

on complex terrains,

819
00:32:35,130 --> 00:32:36,500
like--like a mountain goat does,
right?

820
00:32:36,500 --> 00:32:38,200
We can go anywhere, right.

821
00:32:38,200 --> 00:32:39,630
It's just like, there's science,
let's go there, okay.

822
00:32:39,630 --> 00:32:41,930
We've got a mountain goat,
let's do it, all right.

823
00:32:41,930 --> 00:32:43,300
And what do you see
in this quality?

824
00:32:43,300 --> 00:32:45,400
This is just sort of passively
being poked right now.

825
00:32:45,400 --> 00:32:46,930
This is just
the passive structure.

826
00:32:46,930 --> 00:32:48,600
And it has exactly
what you want, right?

827
00:32:48,600 --> 00:32:50,130
It is a stable structure.

828
00:32:50,130 --> 00:32:52,170
It's able to hold itself up.

829

00:32:52,170 --> 00:32:53,800
And yet, at the same time,
if you poke it,

830
00:32:53,800 --> 00:32:56,100
if you prod it, if you drop it,
it responds.

831
00:32:56,100 --> 00:32:59,230
It adapts.
It's really nice and compliant.

832
00:32:59,230 --> 00:33:01,570
And so we took it

833
00:33:01,570 --> 00:33:03,770
and then in the simulator

834
00:33:03,770 --> 00:33:06,770
dropped it onto a variety of
random block fields.

835
00:33:06,770 --> 00:33:09,030
And what we found is that
it adapts really nicely.

836
00:33:09,030 --> 00:33:10,870
I especially like this one
over here,

837
00:33:10,870 --> 00:33:14,700
where it's on the sort of
cross body of blocks.

838
00:33:14,700 --> 00:33:16,470
And that's just it passively
and naturally

839
00:33:16,470 --> 00:33:19,070
redistributing its load

840
00:33:19,070 --> 00:33:20,430
and rebalancing itself.

841
00:33:20,430 --> 00:33:22,400
No control was used
to make that happen.

842
00:33:22,400 --> 00:33:23,700
And it's possible, right?

843
00:33:23,700 --> 00:33:25,600
A normal robot with a rigid
torso would fall over

844
00:33:25,600 --> 00:33:27,200
in a situation like this.

845
00:33:27,200 --> 00:33:29,770
This is possible because of
the flexible spine

846
00:33:29,770 --> 00:33:32,400
that allows all the forces of
contact to be integrated,

847
00:33:32,400 --> 00:33:35,300
twisted, rotated,
whatever needs to be done.

848
00:33:35,300 --> 00:33:37,070
And that's what you are really
gonna need

849
00:33:37,070 --> 00:33:38,530
if you want to be able to
clamber over

850
00:33:38,530 --> 00:33:40,670

really complex things
and, you know,

851
00:33:40,670 --> 00:33:42,530
stem up some rock face

852
00:33:42,530 --> 00:33:45,470
and still control
how your forces

853
00:33:45,470 --> 00:33:49,000
are pushing into the ground
so that you don't slip and fall.

854
00:33:49,000 --> 00:33:51,770
Other folks at UC Santa Cruz
that I collaborate with

855
00:33:51,770 --> 00:33:54,700
are also then looking at arms
and legs and shoulders, right.

856
00:33:54,700 --> 00:33:56,500
Our shoulders are
really amazing joints.

857
00:33:56,500 --> 00:33:57,870
These are big, spherical joints

858
00:33:57,870 --> 00:34:00,600
with really complex
ranges of motion.

859
00:34:00,600 --> 00:34:02,730
So they're trying to explore how
you can build robots

860
00:34:02,730 --> 00:34:05,230
that take this advantage--

861
00:34:05,230 --> 00:34:06,870
take advantage of
this tensegrity principle

862
00:34:06,870 --> 00:34:09,400
and give you
those ranges of motion.

863
00:34:09,400 --> 00:34:11,530
But as I said,

864
00:34:11,530 --> 00:34:12,970
you know, that's sort of
the far future

865
00:34:12,970 --> 00:34:14,500
early sort of research

866
00:34:14,500 --> 00:34:16,670
mostly in collaboration
with other folks to--

867
00:34:16,670 --> 00:34:18,600
to see what's possible,

868
00:34:18,600 --> 00:34:20,730
but the other big question is,
how do you control these things?

869
00:34:20,730 --> 00:34:22,770
And as I mentioned
at the beginning,

870
00:34:22,770 --> 00:34:24,700
they're--these structures are
oscillatory.

871
00:34:24,700 --> 00:34:26,770
They want to move.

They vibrate.

872
00:34:26,770 --> 00:34:29,900
If you go to that big
art structure at Stanford,

873
00:34:29,900 --> 00:34:31,270
the tensegrity structure,

874
00:34:31,270 --> 00:34:32,970
and you happen to be there
late at night

875
00:34:32,970 --> 00:34:35,730
and you push on it
rhythmically for a while,

876
00:34:35,730 --> 00:34:38,030
you'll find this thing
that looks pretty static

877
00:34:38,030 --> 00:34:40,870
and it's pretty giant and
it'll--it starts moving, right.

878
00:34:40,870 --> 00:34:43,330
You're like, okay, that's--maybe
I don't want that for my house.

879
00:34:43,330 --> 00:34:44,830
Right?
[laughter]

880
00:34:44,830 --> 00:34:46,070
So how do I control this, right.

881
00:34:46,070 --> 00:34:49,270
If you talk to your average
controls engineer,

882
00:34:49,270 --> 00:34:51,100
maybe an airplane designer,
they'll be like,

883
00:34:51,100 --> 00:34:52,630
"Oh, yeah, oscillations,
those are bad.

884
00:34:52,630 --> 00:34:54,900
Yeah, we don't want any of those
in our structures."

885
00:34:54,900 --> 00:34:56,130
[laughs]

886
00:34:56,130 --> 00:34:57,470
They make the plane explode,
right?

887
00:34:57,470 --> 00:34:58,930
And--and they're true.

888
00:34:58,930 --> 00:35:01,670
Uncontrolled oscillation is
a really bad thing.

889
00:35:01,670 --> 00:35:04,030
If you can't sense it
and you can't control it,

890
00:35:04,030 --> 00:35:05,770
that's causes trouble, right?

891
00:35:05,770 --> 00:35:09,170
Then you can get into runaway
oscillation and resonances.

892
00:35:09,170 --> 00:35:11,030
But if you can control it,

893
00:35:11,030 --> 00:35:13,200
if you can sense the oscillation

894
00:35:13,200 --> 00:35:14,630
and you can control it,

895
00:35:14,630 --> 00:35:17,700
there's a lot of variancing
things you can do with it.

896
00:35:17,700 --> 00:35:19,830
And beyond just oscillation,

897
00:35:19,830 --> 00:35:23,330
these are complex nonlinear
systems, that really sort of

898
00:35:23,330 --> 00:35:25,800
very limited design
and engineering tools for us.

899
00:35:25,800 --> 00:35:28,000
So we're really sort of at
the beginning of figuring out

900
00:35:28,000 --> 00:35:29,470
how to make this all work.

901
00:35:29,470 --> 00:35:31,500
So again, let's turn to biology.

902
00:35:31,500 --> 00:35:32,930
Everything we do it rhythmic.

903
00:35:32,930 --> 00:35:35,070
Very basic things,
your heartbeat, rhythmic.

904
00:35:35,070 --> 00:35:38,100
How you eat, chewing
is a very rhythmic thing.

905
00:35:38,100 --> 00:35:39,500
How we talk with each other,

906
00:35:39,500 --> 00:35:41,800
everything from the phonemes,
the basic sounds,

907
00:35:41,800 --> 00:35:43,400
those are, you know,
frequency based,

908
00:35:43,400 --> 00:35:46,100
to high-level dialogue.

909
00:35:46,100 --> 00:35:47,470
If I...

910
00:35:47,470 --> 00:35:49,130
started talking very...

911
00:35:49,130 --> 00:35:50,570
randomly and differently,

912
00:35:50,570 --> 00:35:52,170
you'd think it was
kind of weird, right?

913
00:35:52,170 --> 00:35:54,730
Rhythm matters to how we even
engage with each other.

914
00:35:54,730 --> 00:35:57,400
Dancing, we love that,
singing, walking,

915
00:35:57,400 --> 00:35:59,770
the basics of motion,
all these things are rhythmic.

916
00:35:59,770 --> 00:36:02,030
And then,
the most important of all,

917
00:36:02,030 --> 00:36:04,030
your breathing, I hope.

918
00:36:04,030 --> 00:36:06,330
And therefore everything you do
is rhythmic.

919
00:36:06,330 --> 00:36:08,000
So here's a quick experiment
for you to try.

920
00:36:08,000 --> 00:36:09,970
So this also
will keep you awake.

921
00:36:09,970 --> 00:36:11,630
Sort of sit up a little bit
so you're not slouched

922
00:36:11,630 --> 00:36:15,030
into your chair,
and stick your finger out.

923
00:36:15,030 --> 00:36:17,900
Maybe don't poke anyone,
unless they--they want you to,

924
00:36:17,900 --> 00:36:20,500
but, you know, point your finger
at something

925

00:36:20,500 --> 00:36:22,530
and you think, okay, now look,
I'm gonna hold my finger still,

926
00:36:22,530 --> 00:36:24,170
and that's not rhythmic, right?

927
00:36:24,170 --> 00:36:26,130
Look, I'm holding
my finger still.

928
00:36:26,130 --> 00:36:27,900
Now, take some deep breaths...
[inhales deeply]

929
00:36:27,900 --> 00:36:29,670
and keep holding
that finger still.

930
00:36:29,670 --> 00:36:30,900
[exhales sharply]
Notice your chest.

931
00:36:30,900 --> 00:36:32,630
Notice your upper body.

932
00:36:32,630 --> 00:36:35,700
It's moving as you take
those breaths.

933
00:36:35,700 --> 00:36:37,800
So even though you're holding
your finger still,

934
00:36:37,800 --> 00:36:40,400
your arm and your upper body,
all those muscles

935
00:36:40,400 --> 00:36:43,470
are having to actuate

and organize themselves

936
00:36:43,470 --> 00:36:45,230
in a rhythmic manner to
counteract the fact

937
00:36:45,230 --> 00:36:46,570
that you're breathing.

938
00:36:46,570 --> 00:36:48,300
So the very fact that you can
hold yourself still,

939
00:36:48,300 --> 00:36:50,400
or at least some part
of your body still,

940
00:36:50,400 --> 00:36:52,030
requires rhythmic control.

941
00:36:52,030 --> 00:36:53,970
Because you're breathing,
everything is rhythmic.

942
00:36:53,970 --> 00:36:56,030
And I really hope
you don't stop breathing.

943
00:36:56,030 --> 00:36:57,500
[laughter]

944
00:36:57,500 --> 00:36:59,830
So here's--here's
another experiment.

945
00:36:59,830 --> 00:37:03,370
If you guys could all clap
together in unison, without--

946

00:37:03,370 --> 00:37:05,330
I'm not gonna lead.
I'm not gonna show you how.

947
00:37:05,330 --> 00:37:06,600
I think you can do it.

948
00:37:06,600 --> 00:37:07,630
All right, go ahead
and give it a try.

949
00:37:07,630 --> 00:37:08,730
Just start clapping in unison.

950
00:37:08,730 --> 00:37:11,070
[applause]

951
00:37:11,070 --> 00:37:13,470
[rhythmic clapping]

952
00:37:13,470 --> 00:37:15,930
Thank you, thank you.

953
00:37:15,930 --> 00:37:17,630
All right, I like
to get that done early

954
00:37:17,630 --> 00:37:19,170
'cause I don't know what's gonna
happen at the end of the talk.

955
00:37:19,170 --> 00:37:20,930
[laughter]

956
00:37:20,930 --> 00:37:23,200
But--but that's interesting,
right?

957
00:37:23,200 --> 00:37:24,470

No one was telling you
how to do that

958
00:37:24,470 --> 00:37:26,170
yet you did.

959
00:37:26,170 --> 00:37:28,530
So this turns out to be
a really important principle

960
00:37:28,530 --> 00:37:30,630
that rhythmic things

961
00:37:30,630 --> 00:37:33,030
that share some energy
can synchronize,

962
00:37:33,030 --> 00:37:35,530
can come into
a coordinated behavior.

963
00:37:35,530 --> 00:37:39,230
So this is everything from--

964
00:37:39,230 --> 00:37:41,100
Let's get both of these going.

965
00:37:41,100 --> 00:37:45,230
everything from metronomes
on a table, right--

966
00:37:45,230 --> 00:37:47,030
Let's get randomly started.

967
00:37:47,030 --> 00:37:50,470
to, this is sort of a simulation
of fireflies flashing,

968
00:37:50,470 --> 00:37:52,200

and there are fireflies in
nature that do this,

969
00:37:52,200 --> 00:37:54,530
where they all flash in unison,
all right.

970
00:37:54,530 --> 00:37:57,470
And the fireflies,
they don't share a clock

971
00:37:57,470 --> 00:37:59,600
They're not on a--
they're not on an atomic clock.

972
00:37:59,600 --> 00:38:02,200
They don't have a king
or queen firefly, you know.

973
00:38:02,200 --> 00:38:03,900
There's no common bus.

974
00:38:03,900 --> 00:38:05,200
They're just flashing.

975
00:38:05,200 --> 00:38:07,000
Yet, they can synchronize
and behave.

976
00:38:07,000 --> 00:38:08,800
And these metronomes,
what's happening here

977
00:38:08,800 --> 00:38:12,070
is they're--they're moving
but they share some vibration

978
00:38:12,070 --> 00:38:14,500
through the table they're on,
physical vibration.

979
00:38:14,500 --> 00:38:16,900
And because of that small,
minute amount of vibration,

980
00:38:16,900 --> 00:38:18,630
they will eventually
all synchronize.

981
00:38:18,630 --> 00:38:20,130
So this is
a very important property.

982
00:38:20,130 --> 00:38:21,500
It's been studied.

983
00:38:21,500 --> 00:38:23,770
There's a mathematician
at Cornell, Steven Strogatz,

984
00:38:23,770 --> 00:38:25,400
who's written some
really good books about this.

985
00:38:25,400 --> 00:38:29,370
One of them's called "Sync:
How Order Emerges from Chaos."

986
00:38:29,370 --> 00:38:31,300
This is a very, very fundamental
principle.

987
00:38:31,300 --> 00:38:32,730
It's a mathematical principle

988
00:38:32,730 --> 00:38:35,970
independent of the physics
of implementation, right,

989

00:38:35,970 --> 00:38:39,030
as you can see in these two
different videos,

990
00:38:39,030 --> 00:38:41,500
that--that rhythmic systems

991
00:38:41,500 --> 00:38:43,170
that exchanged energy
can synchronize.

992
00:38:43,170 --> 00:38:45,400
And so you find this
all throughout nature,

993
00:38:45,400 --> 00:38:46,900
and it's a really
important thing

994
00:38:46,900 --> 00:38:48,600
because we often hear
about entropy

995
00:38:48,600 --> 00:38:50,600
and how everything is
tending towards disorder.

996
00:38:50,600 --> 00:38:52,800
And then you ask ourselves,
why are we so organized?

997
00:38:52,800 --> 00:38:55,130
I mean, maybe my house
isn't organized,

998
00:38:55,130 --> 00:38:57,100
but why, you know,
we as living things

999
00:38:57,100 --> 00:38:58,730

are highly organized systems.

1000
00:38:58,730 --> 00:39:00,530
How's that come around
if entropy exists?

1001
00:39:00,530 --> 00:39:02,400
Well, it turns out that
because rhythmic systems

1002
00:39:02,400 --> 00:39:05,070
can create order
with no central control,

1003
00:39:05,070 --> 00:39:06,900
not top-down management,

1004
00:39:06,900 --> 00:39:10,370
but purely as an emergent
mathematical property.

1005
00:39:10,370 --> 00:39:11,600
So we find this--

1006
00:39:11,600 --> 00:39:14,200
I'm not gonna wait for that
to synchronize.

1007
00:39:14,200 --> 00:39:16,330
Well, let's here--
It's--

1008
00:39:16,330 --> 00:39:18,970
That just--ahh.

1009
00:39:18,970 --> 00:39:22,200
I'll just show you that
at the end of the video

1010

00:39:22,200 --> 00:39:25,430
it is--

1011
00:39:25,430 --> 00:39:28,130
Come on, do it.

1012
00:39:28,130 --> 00:39:30,100
All right.

1013
00:39:30,100 --> 00:39:33,200
Yeah, there they are.
They all got there, right.

1014
00:39:33,200 --> 00:39:35,300
So and, you know,

1015
00:39:35,300 --> 00:39:37,100
these algorithms are--
are understandable.

1016
00:39:37,100 --> 00:39:38,600
There's lots--you can
go find lots of people

1017
00:39:38,600 --> 00:39:40,270
making synthetic algorithms
for synchronization

1018
00:39:40,270 --> 00:39:41,900
in distributed manners.

1019
00:39:41,900 --> 00:39:43,430
So it turns out
that this is at the heart

1020
00:39:43,430 --> 00:39:45,000
of modern neuroscience, right.

1021
00:39:45,000 --> 00:39:46,800

You've got people like
Gyorgy Buzsaki

1022
00:39:46,800 --> 00:39:49,130
who are really saying that
brains are primarily concerned

1023
00:39:49,130 --> 00:39:51,800
with rhythm, timing,
and temporal prediction.

1024
00:39:51,800 --> 00:39:52,870
And this makes sense.

1025
00:39:52,870 --> 00:39:54,000
If everything is rhythmic,

1026
00:39:54,000 --> 00:39:55,670
and all the other animals
are rhythmic,

1027
00:39:55,670 --> 00:39:57,800
then, you know, you really want
to be able to track

1028
00:39:57,800 --> 00:39:59,270
other rhythmic motions, right.

1029
00:39:59,270 --> 00:40:00,700
The sun's cycle is rhythmic.

1030
00:40:00,700 --> 00:40:02,730
When a--when a particular tree

1031
00:40:02,730 --> 00:40:04,830
is gonna become ripe with fruit
is rhythmic.

1032
00:40:04,830 --> 00:40:08,070

If you're the--if you're the
leopard sitting in a tree branch

1033
00:40:08,070 --> 00:40:10,030
waiting for the gazelle
to pass underneath

1034
00:40:10,030 --> 00:40:11,300
and you want to jump on it,

1035
00:40:11,300 --> 00:40:13,000
you better understand
the rhythm of its motion

1036
00:40:13,000 --> 00:40:14,300
and get your timing just right.

1037
00:40:14,300 --> 00:40:15,770
Otherwise, you're gonna
face-plant

1038
00:40:15,770 --> 00:40:17,000
and miss lunch, right.

1039
00:40:17,000 --> 00:40:18,570
So rhythm's at the heart
of it all,

1040
00:40:18,570 --> 00:40:20,100
and we see this
in neurons, right.

1041
00:40:20,100 --> 00:40:23,870
They are rhythmic, bursting,
oscillatory systems.

1042
00:40:23,870 --> 00:40:27,300
Besides individual neurons,
you have networks of neurons

1043
00:40:27,300 --> 00:40:28,930
that are called
central pattern generators,

1044
00:40:28,930 --> 00:40:30,330
CPGs.

1045
00:40:30,330 --> 00:40:33,700
And this is at the heart of
a lot of modern research

1046
00:40:33,700 --> 00:40:35,570
into mammalian locomotion,

1047
00:40:35,570 --> 00:40:37,800
that these networks of CPGs

1048
00:40:37,800 --> 00:40:41,130
are able to create rhythms
and generate them

1049
00:40:41,130 --> 00:40:42,500
and then interact with
each other

1050
00:40:42,500 --> 00:40:46,300
and coordinate the control of
motors, i.e. muscles,

1051
00:40:46,300 --> 00:40:50,430
and be at the center
of a lot of gait production,

1052
00:40:50,430 --> 00:40:52,330
a lot of the rhythmic
motions that we do,

1053
00:40:52,330 --> 00:40:54,730
everything from chewing

to walking.

1054
00:40:54,730 --> 00:40:58,500
So why are CPGs interesting
then?

1055
00:40:58,500 --> 00:41:00,500
They have a couple
interesting properties, right.

1056
00:41:00,500 --> 00:41:02,600
If you have this
distributed system,

1057
00:41:02,600 --> 00:41:04,930
that is able, from its own
intrinsic dynamics,

1058
00:41:04,930 --> 00:41:08,530
to be able to come up with
an organized rhythmic behavior

1059
00:41:08,530 --> 00:41:10,900
and coordinate its actions,

1060
00:41:10,900 --> 00:41:12,500
then you get a reduction
dimensionality of control,

1061
00:41:12,500 --> 00:41:13,770
right.

1062
00:41:13,770 --> 00:41:16,430
So what would normally be
hundreds of degrees

1063
00:41:16,430 --> 00:41:18,630
of--of--of muscles that need
to be coordinated,

1064
00:41:18,630 --> 00:41:21,730
you can simplify that down
to a much simpler problem.

1065
00:41:21,730 --> 00:41:24,530
And one of the things
that I see

1066
00:41:24,530 --> 00:41:27,970
in tensegrity structures
and in CPGs,

1067
00:41:27,970 --> 00:41:30,430
if you dive into the how that
control works

1068
00:41:30,430 --> 00:41:32,170
how information passes through
a network

1069
00:41:32,170 --> 00:41:34,570
of these rhythmic controllers,

1070
00:41:34,570 --> 00:41:36,930
it ends up being very adaptable
and compliant

1071
00:41:36,930 --> 00:41:39,930
in much the same way that
these tensegrity structures

1072
00:41:39,930 --> 00:41:41,370
are adaptable and compliant

1073
00:41:41,370 --> 00:41:43,630
to the forces
they are experiencing.

1074
00:41:43,630 --> 00:41:46,730

So in terms of that
reduction of complexity,

1075
00:41:46,730 --> 00:41:49,630
here is a 30-segment spine

1076
00:41:49,630 --> 00:41:52,300
that's running using
a bunch of these CPGs.

1077
00:41:52,300 --> 00:41:54,430
Each cable has its own
CPG controller.

1078
00:41:54,430 --> 00:41:58,700
A--for reference, a dog has
32 segments in its spine.

1079
00:41:58,700 --> 00:42:00,230
So this has, overall,

1080
00:42:00,230 --> 00:42:03,100
232 different individually
controlled muscles.

1081
00:42:03,100 --> 00:42:06,470
If you try to do this with
traditional inverse kinematics

1082
00:42:06,470 --> 00:42:08,200
or other forms
of robotic control,

1083
00:42:08,200 --> 00:42:10,230
you would just break
every machine

1084
00:42:10,230 --> 00:42:11,470
you could throw at it, right?

1085
00:42:11,470 --> 00:42:13,030
It would be way too complicated,

1086
00:42:13,030 --> 00:42:15,400
and that's why you don't see
robots with complex spines.

1087
00:42:15,400 --> 00:42:17,170
Yet, here we are
controlling this

1088
00:42:17,170 --> 00:42:18,930
computationally very efficiently

1089
00:42:18,930 --> 00:42:23,030
because it is a distributed,
very simple form of control

1090
00:42:23,030 --> 00:42:25,430
that allows its coordination
to come

1091
00:42:25,430 --> 00:42:28,400
as an intrinsic property
of its rhythm.

1092
00:42:28,400 --> 00:42:30,670
So then the question is,
you can push this out,

1093
00:42:30,670 --> 00:42:32,770
you can use a bunch of
sine waves to make these rhythms

1094
00:42:32,770 --> 00:42:34,730
and have them, you know,
move in that way,

1095
00:42:34,730 --> 00:42:36,870

but what's more important is
when you close the loop.

1096
00:42:36,870 --> 00:42:40,200
When you take your--
Up at the top,

1097
00:42:40,200 --> 00:42:42,630
we have the--the actual
low-level controllers.

1098
00:42:42,630 --> 00:42:44,570
You have the physics model
at the bottom.

1099
00:42:44,570 --> 00:42:46,230
You get some sensor information
about length,

1100
00:42:46,230 --> 00:42:48,130
tension, velocity,

1101
00:42:48,130 --> 00:42:50,570
and then we pass it through
a very simple neural network

1102
00:42:50,570 --> 00:42:53,030
to close the loop
back into that CPG,

1103
00:42:53,030 --> 00:42:55,400
so now that--you start
actually getting feedback

1104
00:42:55,400 --> 00:42:56,800
from the environment.

1105
00:42:56,800 --> 00:42:58,800
And what you see here,
right now, the feedback is off.

1106
00:42:58,800 --> 00:43:00,430
This is what we call
open-loop control.

1107
00:43:00,430 --> 00:43:02,700
We're just sort of commanding
the robot to move.

1108
00:43:02,700 --> 00:43:04,300
And when we turn on
the feedback,

1109
00:43:04,300 --> 00:43:06,900
which just happened, you'll see
that its gait cycle changes,

1110
00:43:06,900 --> 00:43:08,130
and now you start getting a gait

1111
00:43:08,130 --> 00:43:10,330
that's a much larger
amplitude gait,

1112
00:43:10,330 --> 00:43:13,100
and it's really tuning to
the coupled dynamics

1113
00:43:13,100 --> 00:43:16,170
of the robot interacting
with this environment.

1114
00:43:16,170 --> 00:43:18,430
And that's that natural tendency

1115
00:43:18,430 --> 00:43:20,270
to just couple with
the environment

1116

00:43:20,270 --> 00:43:21,530
and with the actual
structure itself,

1117
00:43:21,530 --> 00:43:23,030
which makes
this control approach

1118
00:43:23,030 --> 00:43:24,870
so flexible
and dynamic.

1119
00:43:24,870 --> 00:43:28,170
You don't have to understand
the external reality perfectly.

1120
00:43:28,170 --> 00:43:30,270
Rather, it's just based on
the forces and experience

1121
00:43:30,270 --> 00:43:32,070
of its own motion.

1122
00:43:32,070 --> 00:43:35,300
It's gonna find an efficient way
to continue to move.

1123
00:43:35,300 --> 00:43:37,700
Then we have
the final question of--

1124
00:43:37,700 --> 00:43:39,800
That's all great.
You got these robots moving.

1125
00:43:39,800 --> 00:43:41,930
They're moving across, you know,
fields of flat ground

1126
00:43:41,930 --> 00:43:43,930

or lumpy ground or whatever,
but how do you do something?

1127
00:43:43,930 --> 00:43:46,700
How do you actually make it go
accomplish some goal?

1128
00:43:46,700 --> 00:43:49,830
And this is where the brain
comes back in finally, right?

1129
00:43:49,830 --> 00:43:52,670
The--the brain that we took off
at the beginning,

1130
00:43:52,670 --> 00:43:56,400
we actually started putting
a layer of more--

1131
00:43:56,400 --> 00:43:59,170
artificial neurons on there
where we start looking at a goal

1132
00:43:59,170 --> 00:44:01,630
and start saying, what's
our direction to that goal?

1133
00:44:01,630 --> 00:44:04,170
And using that
to influence

1134
00:44:04,170 --> 00:44:07,830
how the central pattern
generator works, right,

1135
00:44:07,830 --> 00:44:10,070
what direction it's going,
and what you'll see...

1136
00:44:10,070 --> 00:44:12,000

I'm gonna start
all these videos.

1137
00:44:12,000 --> 00:44:14,530
is that across a variety
of different terrains

1138
00:44:14,530 --> 00:44:16,270
and a variety
of different goals,

1139
00:44:16,270 --> 00:44:19,230
we eventually were able
to get these robots

1140
00:44:19,230 --> 00:44:22,870
to drive to
these goal targets.

1141
00:44:22,870 --> 00:44:25,300
And it's pretty much--it's just
pretty much doing the steering.

1142
00:44:25,300 --> 00:44:27,470
It's not trying to control
all the individual muscles,

1143
00:44:27,470 --> 00:44:29,070
like you would on
a traditional robot.

1144
00:44:29,070 --> 00:44:30,730
Rather, we're saying,
go a little more left,

1145
00:44:30,730 --> 00:44:31,930
go a little more right,
the goal's over there.

1146
00:44:31,930 --> 00:44:33,270

That's where
we're trying to go.

1147
00:44:33,270 --> 00:44:35,000
It's just kind of
straightforward visual servoing

1148
00:44:35,000 --> 00:44:37,230
if you will,
but with the very complex

1149
00:44:37,230 --> 00:44:40,070
underlying distributed system
that manages all the details

1150
00:44:40,070 --> 00:44:41,770
of the physical interaction
within our environment

1151
00:44:41,770 --> 00:44:43,370
so you don't have to do that all
in your brain.

1152
00:44:43,370 --> 00:44:44,870
My head would hurt
if I had to think about

1153
00:44:44,870 --> 00:44:48,500
every little bit of force and
contact that I needed to control

1154
00:44:48,500 --> 00:44:52,930
in order to operate
this computer, for instance.

1155
00:44:52,930 --> 00:44:55,270
So that's the big part
of the story,

1156
00:44:55,270 --> 00:44:56,830

and it brings us back to
the brain, right.

1157
00:44:56,830 --> 00:44:58,370
And this is where we get to
the fun part of it all.

1158
00:44:58,370 --> 00:45:00,930
Why do science
if you don't have philosophy?

1159
00:45:00,930 --> 00:45:03,600
And--which is this.

1160
00:45:03,600 --> 00:45:06,770
You know, we tend to use the
current technology of the day

1161
00:45:06,770 --> 00:45:09,170
as our model for how
we think about things, right?

1162
00:45:09,170 --> 00:45:11,070
So we tend to think about
our brains like the CPUs

1163
00:45:11,070 --> 00:45:13,270
of our computers, 'cause that's
today's technology.

1164
00:45:13,270 --> 00:45:15,530
But what this talk hopefully
might have shown you

1165
00:45:15,530 --> 00:45:17,600
is that you have a computational
system in your head

1166
00:45:17,600 --> 00:45:19,930
that is perhaps built around

synchronization

1167
00:45:19,930 --> 00:45:22,200
rather than on
binary logical flows, right.

1168
00:45:22,200 --> 00:45:24,630
The fact that we can do math
is amazing,

1169
00:45:24,630 --> 00:45:26,130
but we don't necessarily
use math

1170
00:45:26,130 --> 00:45:28,370
at the basis of our brains,
other than the fact

1171
00:45:28,370 --> 00:45:31,230
that synchronization is
a mathematical property but...

1172
00:45:31,230 --> 00:45:33,570
So what are some of the things
that come out of this, right?

1173
00:45:33,570 --> 00:45:36,870
If you have a system built
around synchronization,

1174
00:45:36,870 --> 00:45:40,430
you see qualities that are
very hard for us

1175
00:45:40,430 --> 00:45:42,670
to accomplish in traditional
AI techniques.

1176
00:45:42,670 --> 00:45:44,300
Everything from

pattern recognition,

1177
00:45:44,300 --> 00:45:46,230
seeing a bunch of things
being similar, right?

1178
00:45:46,230 --> 00:45:47,470
It's very hard.

1179
00:45:47,470 --> 00:45:49,300
Some of the deep learning
algorithms of today

1180
00:45:49,300 --> 00:45:51,100
are starting to be able to
accomplish this.

1181
00:45:51,100 --> 00:45:53,370
But associations,
like connections.

1182
00:45:53,370 --> 00:45:54,470
What do humans love to do?

1183
00:45:54,470 --> 00:45:56,030
We love to connect
with each other.

1184
00:45:56,030 --> 00:45:59,530
We love to make new friends and
just resonate with each other.

1185
00:45:59,530 --> 00:46:01,130
And what else do we do,
you know?

1186
00:46:01,130 --> 00:46:03,000
We--we--if you move somewhere,

1187

00:46:03,000 --> 00:46:05,570
if you, say, move to Georgia
and live there for a few years,

1188
00:46:05,570 --> 00:46:07,130
you would pick up
a Southern drawl.

1189
00:46:07,130 --> 00:46:08,670
It--it's almost impossible
to stop.

1190
00:46:08,670 --> 00:46:10,930
We synchronize with the people
around us.

1191
00:46:10,930 --> 00:46:13,070
We become like the people
we hang out with.

1192
00:46:13,070 --> 00:46:15,470
You develop a new group
of friends,

1193
00:46:15,470 --> 00:46:16,830
you might start
dressing like them,

1194
00:46:16,830 --> 00:46:19,930
putting on funny party hats,
whatever they do.

1195
00:46:19,930 --> 00:46:23,100
And--or--or, you know,
there's a very good chance

1196
00:46:23,100 --> 00:46:24,930
that you share a lot of
the same political views

1197

00:46:24,930 --> 00:46:27,200
as the people that you love
and trust the most, right?

1198
00:46:27,200 --> 00:46:28,570
That's just part of what we do.

1199
00:46:28,570 --> 00:46:30,170
We synchronize
with those around us.

1200
00:46:30,170 --> 00:46:33,270
So we start seeing
a lot of these qualities

1201
00:46:33,270 --> 00:46:36,270
that are very human, high level,
social interaction qualities

1202
00:46:36,270 --> 00:46:39,700
having the same
underlying drivers

1203
00:46:39,700 --> 00:46:42,570
as we see in the basis of
how do we move our bodies

1204
00:46:42,570 --> 00:46:43,600
through the world.

1205
00:46:43,600 --> 00:46:45,770
This quality of rhythm
and synchronization

1206
00:46:45,770 --> 00:46:47,770
and the fact that
we like to dance,

1207
00:46:47,770 --> 00:46:49,530
unless we're too embarrassed

by ourselves,

1208
00:46:49,530 --> 00:46:51,870
but that's its own problem.

1209
00:46:51,870 --> 00:46:54,000
So anyways,

1210
00:46:54,000 --> 00:46:56,930
that's the philosophy
behind all of this, you know.

1211
00:46:56,930 --> 00:46:59,400
Hopefully it also helps us go
explore the solar system.

1212
00:46:59,400 --> 00:47:01,730
And I did not do this alone.

1213
00:47:01,730 --> 00:47:04,400
Here are at least a small
portion of the people

1214
00:47:04,400 --> 00:47:05,670
who have helped me
along the way.

1215
00:47:05,670 --> 00:47:07,930
These were students
from summer of 2014,

1216
00:47:07,930 --> 00:47:10,230
and I really need to make
a new photo of that this summer

1217
00:47:10,230 --> 00:47:13,670
of all the other new people
who have really helped out

1218

00:47:13,670 --> 00:47:15,230
building this vision.

1219
00:47:15,230 --> 00:47:17,000
And so thanks
to all of them,

1220
00:47:17,000 --> 00:47:19,170
and thanks to you
for listening.

1221
00:47:19,170 --> 00:47:20,870
And that's my talk.

1222
00:47:20,870 --> 00:47:25,570
[applause]

1223
00:47:25,570 --> 00:47:29,170
- Thank you.
Nice talk.

1224
00:47:29,170 --> 00:47:30,630
So we have time for
a few questions.

1225
00:47:30,630 --> 00:47:32,830
If you have a question,
please raise your hand,

1226
00:47:32,830 --> 00:47:33,770
wait for a microphone,

1227
00:47:33,770 --> 00:47:36,670
and then ask
one question only.

1228
00:47:36,670 --> 00:47:37,830
Go ahead, right there.

1229

00:47:37,830 --> 00:47:39,370
- I am so delighted
to hear all of this.

1230
00:47:39,370 --> 00:47:40,800
I thought that nobody else
in the world

1231
00:47:40,800 --> 00:47:42,600
was thinking about brains
and bodies

1232
00:47:42,600 --> 00:47:44,670
and oscillators and stuff
in this way,

1233
00:47:44,670 --> 00:47:46,700
and you're way closer to
the ground truth.

1234
00:47:46,700 --> 00:47:48,730
You're actually building it
and it's working.

1235
00:47:48,730 --> 00:47:52,700
My approach is information
science, theoretical physics,

1236
00:47:52,700 --> 00:47:55,200
and algorithms
and stuff like that,

1237
00:47:55,200 --> 00:47:56,530
so I've been working
in the valley.

1238
00:47:56,530 --> 00:47:58,070
So I'd like to offer
a couple of predictions...

1239

00:47:58,070 --> 00:48:00,230
I know far too much about it
to call 'em questions.

1240
00:48:00,230 --> 00:48:02,300
about where this project
is going

1241
00:48:02,300 --> 00:48:04,500
and why it's gonna be
so wonderful.

1242
00:48:04,500 --> 00:48:07,500
It's exactly the right way
of taking it apart.

1243
00:48:07,500 --> 00:48:09,170
Tensegrity is a beautiful
sort of thing,

1244
00:48:09,170 --> 00:48:12,330
and when you make it big enough,
it paradoxically gets simpler.

1245
00:48:12,330 --> 00:48:15,500
You were talking about
232 classical robotic

1246
00:48:15,500 --> 00:48:18,700
sort of hinge variables
down to 30 segments.

1247
00:48:18,700 --> 00:48:21,200
Well, once you get, like,
a zillion segments,

1248
00:48:21,200 --> 00:48:23,030
it's now just
a three-dimensional structure.

1249

00:48:23,030 --> 00:48:26,670
So you're gonna find yourself
solving continuous equations,

1250
00:48:26,670 --> 00:48:29,700
as if it were Gumby,
and continuous vibrations.

1251
00:48:29,700 --> 00:48:32,670
The other prediction is that
you're gonna find

1252
00:48:32,670 --> 00:48:34,730
all the interesting stuff
at the very highest bandwidth.

1253
00:48:34,730 --> 00:48:37,470
When you look for
central pattern recognition,

1254
00:48:37,470 --> 00:48:39,970
that tends to synchronize,
and it's kind of slow.

1255
00:48:39,970 --> 00:48:41,900
There's not much information
flow in a pendulum

1256
00:48:41,900 --> 00:48:43,430
once it starts swinging.

1257
00:48:43,430 --> 00:48:45,530
But all the tiny little ripples

1258
00:48:45,530 --> 00:48:47,500
from our million
mechanoreceptors

1259
00:48:47,500 --> 00:48:49,170
and our million muscle fibers,

1260
00:48:49,170 --> 00:48:50,570
it's like a 3-D tomography
problem

1261
00:48:50,570 --> 00:48:53,900
with, you know, a million little
firecrackers going off

1262
00:48:53,900 --> 00:48:56,870
and the brain has to gather
all those vibrations somehow

1263
00:48:56,870 --> 00:48:59,100
and make sense of it in 3-D.

1264
00:48:59,100 --> 00:49:00,700
So ultimately,
once you solve that,

1265
00:49:00,700 --> 00:49:01,770
you're gonna understand yoga,

1266
00:49:01,770 --> 00:49:03,400
you're gonna understand
acupuncture,

1267
00:49:03,400 --> 00:49:05,630
because you're going to
understand bodies.

1268
00:49:05,630 --> 00:49:08,300
as megahertz-level
vibrating instruments.

1269
00:49:08,300 --> 00:49:09,730
You can hear the tremor
in my voice.

1270

00:49:09,730 --> 00:49:11,370
It's kind of obvious, right?

1271
00:49:11,370 --> 00:49:13,470
But you'll also understand
our communication,

1272
00:49:13,470 --> 00:49:15,730
not as merely the syncing
of pendulums

1273
00:49:15,730 --> 00:49:18,170
but as chaos-control ripples

1274
00:49:18,170 --> 00:49:20,730
in which the very vibrations
from inside my body

1275
00:49:20,730 --> 00:49:23,630
are being felt by everyone.

1276
00:49:23,630 --> 00:49:28,000
- Thank you.

1277
00:49:28,000 --> 00:49:31,030
- I had a question
regarding the motion.

1278
00:49:31,030 --> 00:49:33,630
How do you control--
like, have you tried

1279
00:49:33,630 --> 00:49:35,670
a downhill motion of the robot?

1280
00:49:35,670 --> 00:49:37,970
Because--because it seems
unstable right now

1281

00:49:37,970 --> 00:49:40,000
because it's pivoting at
one or two points

1282
00:49:40,000 --> 00:49:41,830
and it's just rolling down.

1283
00:49:41,830 --> 00:49:43,100
So have you already figured out

1284
00:49:43,100 --> 00:49:46,300
how you'll control
the downhill motion?

1285
00:49:46,300 --> 00:49:49,000
- Yeah, so the--the way--

1286
00:49:49,000 --> 00:49:51,170
Like, I showed you both just
rolling it down a hill

1287
00:49:51,170 --> 00:49:52,870
in a passive way,

1288
00:49:52,870 --> 00:49:55,100
and then I also showed
some videos of it

1289
00:49:55,100 --> 00:49:57,130
just rolling over
on flat ground.

1290
00:49:57,130 --> 00:50:00,870
And the way SUPERball is
locomoting right now

1291
00:50:00,870 --> 00:50:03,930
is that it is moving
its center of mass

1292
00:50:03,930 --> 00:50:06,930
over the polygon of support
of its feet

1293
00:50:06,930 --> 00:50:08,630
until it falls over,
much like us.

1294
00:50:08,630 --> 00:50:11,930
I mean, we--we--we move by
falling over our support base

1295
00:50:11,930 --> 00:50:13,330
and then catching ourselves.

1296
00:50:13,330 --> 00:50:15,470
So it has that similar quality

1297
00:50:15,470 --> 00:50:18,030
of moving its center of mass
and then--

1298
00:50:18,030 --> 00:50:20,170
and then causing that
to be a dynamic motion.

1299
00:50:20,170 --> 00:50:23,400
So if you want to slow it down
while going downhill,

1300
00:50:23,400 --> 00:50:25,030
you would want to move
your center of mass

1301
00:50:25,030 --> 00:50:28,070
towards the uphill
so that you could,

1302
00:50:28,070 --> 00:50:29,770

you know, control that slightly.

1303
00:50:29,770 --> 00:50:31,800
Now, that being said,

1304
00:50:31,800 --> 00:50:34,400
it may not be the best at really
having controlled descent

1305
00:50:34,400 --> 00:50:35,700
down a really steep hill,

1306
00:50:35,700 --> 00:50:38,170
but the thing to remember is
that this is a robot

1307
00:50:38,170 --> 00:50:40,370
that, hopefully, will
safely fall from orbit.

1308
00:50:40,370 --> 00:50:43,630
So if it tumbles down a hill

1309
00:50:43,630 --> 00:50:45,600
in a somewhat dynamic manner,

1310
00:50:45,600 --> 00:50:47,530
it is not necessarily gonna be
the end of the mission

1311
00:50:47,530 --> 00:50:49,070
like it would
in a traditional Rover, right.

1312
00:50:49,070 --> 00:50:51,500
This is gonna be something
that it could handle

1313
00:50:51,500 --> 00:50:52,870

as--as a structure.

1314
00:50:52,870 --> 00:50:54,930
So the other thing--
point to remember is

1315
00:50:54,930 --> 00:50:56,470
SUPERball is the beginning,

1316
00:50:56,470 --> 00:50:58,000
and I think in and of itself

1317
00:50:58,000 --> 00:51:01,070
it has some real potential value

1318
00:51:01,070 --> 00:51:04,070
exactly as it is
as a flight mission

1319
00:51:04,070 --> 00:51:06,470
when we have continued to build
the technologies further.

1320
00:51:06,470 --> 00:51:08,270
But there's a lot more--

1321
00:51:08,270 --> 00:51:09,970
a lot of variations
you could build on this, right.

1322
00:51:09,970 --> 00:51:11,670
Instead of just being six bars,

1323
00:51:11,670 --> 00:51:14,370
you could have a version of it
that has 12 or 30 bars

1324
00:51:14,370 --> 00:51:15,670
or whatever,

1325
00:51:15,670 --> 00:51:18,330
and then that starts becoming
more like a real sphere

1326
00:51:18,330 --> 00:51:19,630
that you can deform even further

1327
00:51:19,630 --> 00:51:22,070
and you could flatten it down to
look more like a tread

1328
00:51:22,070 --> 00:51:24,200
or, you know, change its--
its body shape

1329
00:51:24,200 --> 00:51:26,870
and change its ground contact
surface a lot more.

1330
00:51:26,870 --> 00:51:29,100
That's obviously a much more
complicated mechanism

1331
00:51:29,100 --> 00:51:33,570
that would stretch the limited
budget that I've had

1332
00:51:33,570 --> 00:51:35,200
in terms of building it.

1333
00:51:35,200 --> 00:51:36,730
So we're working with
the simplest one

1334
00:51:36,730 --> 00:51:38,930
we can possibly make
that has a fewer number

1335

00:51:38,930 --> 00:51:40,500
of motors and components in it.

1336
00:51:40,500 --> 00:51:42,570
But down the road, we will be
opening up that exploration,

1337
00:51:42,570 --> 00:51:44,630
which is also why I'm exploring
the legged robots,

1338
00:51:44,630 --> 00:51:48,370
because they will have
even better abilities

1339
00:51:48,370 --> 00:51:50,930
to manage complex terrains
than SUPERball has.

1340
00:51:50,930 --> 00:51:53,670
And so somewhere
in all of that design space

1341
00:51:53,670 --> 00:51:56,670
will be the perfect balance
between

1342
00:51:56,670 --> 00:51:58,770
shock absorption for landing

1343
00:51:58,770 --> 00:52:01,030
and trainability for
exploration.

1344
00:52:01,030 --> 00:52:02,570
And when you get to
the trade studies of

1345
00:52:02,570 --> 00:52:04,100
what do we want to do

for a particular mission,

1346
00:52:04,100 --> 00:52:05,500
that's when you start sort of
figuring out

1347
00:52:05,500 --> 00:52:13,470
where in that design space
you really want to go.

1348
00:52:13,470 --> 00:52:16,670
- Hi, so my question is,

1349
00:52:16,670 --> 00:52:18,670
like, based on your--
the projects you work on

1350
00:52:18,670 --> 00:52:21,600
with the SUPERball,
what's your ultimate goal,

1351
00:52:21,600 --> 00:52:24,530
like, with the project?

1352
00:52:24,530 --> 00:52:26,930
Are you trying to send it up
into space

1353
00:52:26,930 --> 00:52:28,700
and collect information?

1354
00:52:28,700 --> 00:52:31,500
I just--I'm just curious to know
what's your ultimate goal.

1355
00:52:31,500 --> 00:52:33,330
- Well, you know what,
I figure

1356

00:52:33,330 --> 00:52:35,030
why limit yourself to one goal,
right?

1357
00:52:35,030 --> 00:52:36,630
Embrace the power of "and."

1358
00:52:36,630 --> 00:52:38,570
It--it's all of the above,
right.

1359
00:52:38,570 --> 00:52:42,900
I definitely would love to have
this mature

1360
00:52:42,900 --> 00:52:45,630
to the point where we have
a whole new approach

1361
00:52:45,630 --> 00:52:47,500
to doing exploration of
the solar system

1362
00:52:47,500 --> 00:52:49,000
and we can--and--and bring
this technology

1363
00:52:49,000 --> 00:52:51,300
to service in that way.

1364
00:52:51,300 --> 00:52:53,700
And at the same time, as Jacob
hinted at the beginning of this,

1365
00:52:53,700 --> 00:52:55,800
the very quest to--to understand
these things,

1366
00:52:55,800 --> 00:52:57,900
the very quest to imitate

1367
00:52:57,900 --> 00:52:59,870
or be inspired by biology is--

1368
00:52:59,870 --> 00:53:01,870
[coughs]
Pardon me.

1369
00:53:01,870 --> 00:53:04,330
Is also very informative
about ourselves.

1370
00:53:04,330 --> 00:53:07,070
And if we come away
with new ideas

1371
00:53:07,070 --> 00:53:09,030
and new understandings
of how we work--

1372
00:53:09,030 --> 00:53:10,730
I mean, a lot of these theories
I've shown you

1373
00:53:10,730 --> 00:53:12,430
about how the body works
and how the brain works,

1374
00:53:12,430 --> 00:53:13,700
they're out there.

1375
00:53:13,700 --> 00:53:15,170
They're being discussed
and debated

1376
00:53:15,170 --> 00:53:16,570
in different scientific
communities,

1377

00:53:16,570 --> 00:53:18,330
but if we can then say,
hey, look, this is why

1378
00:53:18,330 --> 00:53:21,400
it makes sense to have a body
that's not rigidly connected.

1379
00:53:21,400 --> 00:53:22,630
This is the advantages you get

1380
00:53:22,630 --> 00:53:24,630
because I can build robots
that can do things

1381
00:53:24,630 --> 00:53:26,200
no other robot can do.

1382
00:53:26,200 --> 00:53:28,600
That's gonna tell us something
about how human bodies work,

1383
00:53:28,600 --> 00:53:30,600
and that may inform
how surgeries are done

1384
00:53:30,600 --> 00:53:31,930
and how health care is managed

1385
00:53:31,930 --> 00:53:33,600
and how people take care of
their bodies, right.

1386
00:53:33,600 --> 00:53:35,100
These are very useful things

1387
00:53:35,100 --> 00:53:37,470
that will impact millions of
lives potentially.

1388
00:53:37,470 --> 00:53:39,200
And I would love to see
that impact.

1389
00:53:39,200 --> 00:53:41,170
I'd love to see
our controls research

1390
00:53:41,170 --> 00:53:43,470
to have an influence on how
we understand neuroscience.

1391
00:53:43,470 --> 00:53:47,400
And even beyond that, if this
open up new forms of robotics

1392
00:53:47,400 --> 00:53:49,230
that just impact life
here on Earth,

1393
00:53:49,230 --> 00:53:50,570
that would be great, too, right.

1394
00:53:50,570 --> 00:53:53,670
It doesn't just have to be
the singular quest

1395
00:53:53,670 --> 00:53:55,100
of exploring other planets,

1396
00:53:55,100 --> 00:53:58,470
but that is the real driver
for these projects

1397
00:53:58,470 --> 00:54:01,030
is to build a robot that can go
explore another planet.

1398
00:54:01,030 --> 00:54:03,900

And all the rest of it is part
of the--part of the benefits,

1399
00:54:03,900 --> 00:54:05,830
and that's part of
what NASA does.

1400
00:54:05,830 --> 00:54:08,130
We explore the universe so that
we gain all sorts of knowledge

1401
00:54:08,130 --> 00:54:09,800
that gets used
all over the place.

1402
00:54:09,800 --> 00:54:11,970
Much of your technologies
of your daily life

1403
00:54:11,970 --> 00:54:14,100
are influenced by
prior generations

1404
00:54:14,100 --> 00:54:16,970
of NASA research.

1405
00:54:16,970 --> 00:54:18,830
- Questions?

1406
00:54:18,830 --> 00:54:20,430
- I was wondering if you had
a chance to check out

1407
00:54:20,430 --> 00:54:24,530
Theo Jansen's Strandbeest
exhibit at the Exploratorium.

1408
00:54:24,530 --> 00:54:25,900
- Oh, I haven't seen it
in person.

1409
00:54:25,900 --> 00:54:27,370
I've seen lots of videos
over the years.

1410
00:54:27,370 --> 00:54:28,900
- You can see it in person now
over the summer.

1411
00:54:28,900 --> 00:54:30,430
- Yeah, I just heard this week
about that, so...

1412
00:54:30,430 --> 00:54:33,070
- I noticed that shares
a lot of similarities.

1413
00:54:33,070 --> 00:54:35,000
- Yeah, yeah,
very exciting stuff.

1414
00:54:35,000 --> 00:54:36,730
I look forward to finding a time
to do that.

1415
00:54:36,730 --> 00:54:37,770
Thank you.

1416
00:54:37,770 --> 00:54:39,100
[laughter]

1417
00:54:39,100 --> 00:54:41,130
Time, though, is one of
the tricky parts.

1418
00:54:41,130 --> 00:54:43,070
[laughs]

1419
00:54:43,070 --> 00:54:44,300

- Thank you.

1420
00:54:44,300 --> 00:54:46,770
It's a very fascinating
design idea,

1421
00:54:46,770 --> 00:54:49,070
but I am wondering

1422
00:54:49,070 --> 00:54:51,630
how fast
this thing's gonna be

1423
00:54:51,630 --> 00:54:55,070
and how energy efficient
they--they can be,

1424
00:54:55,070 --> 00:54:56,430
the locomotion.

1425
00:54:56,430 --> 00:55:00,400
And also, if they need to carry
not just themselves,

1426
00:55:00,400 --> 00:55:02,430
but some stable platform,

1427
00:55:02,430 --> 00:55:05,500
like sensors pointing
at certain directions

1428
00:55:05,500 --> 00:55:07,600
all the way
or something like this,

1429
00:55:07,600 --> 00:55:09,730
how can you achieve this?
Thank you.

1430

00:55:09,730 --> 00:55:11,900
- All right, I'll attempt to
answer your four questions.

1431
00:55:11,900 --> 00:55:14,200
[laughs]

1432
00:55:14,200 --> 00:55:17,830
So again,
energy efficiency-wise,

1433
00:55:17,830 --> 00:55:21,000
they--one of the arguments,

1434
00:55:21,000 --> 00:55:22,870
and we are not yet
to the point--

1435
00:55:22,870 --> 00:55:24,570
We're still figuring out
the--the--the basics

1436
00:55:24,570 --> 00:55:26,430
of how to control these, right,
and so I'm not--

1437
00:55:26,430 --> 00:55:28,600
I would not claim that we are at
the point of optimizing

1438
00:55:28,600 --> 00:55:30,930
and maximizing their
energy efficiency yet.

1439
00:55:30,930 --> 00:55:32,300
I'd like to get there someday.

1440
00:55:32,300 --> 00:55:34,200
But one of the theories is that

1441
00:55:34,200 --> 00:55:37,130
if you can control a structure

1442
00:55:37,130 --> 00:55:39,830
at its resonant modes,

1443
00:55:39,830 --> 00:55:42,830
then you get the most energy
efficient means of locomotion

1444
00:55:42,830 --> 00:55:44,470
for that structure.

1445
00:55:44,470 --> 00:55:47,070
And--and that's part of
what we see

1446
00:55:47,070 --> 00:55:49,030
in this combined
flexible structure

1447
00:55:49,030 --> 00:55:53,400
and--and rhythmic
controllers

1448
00:55:53,400 --> 00:55:56,770
is that they do tend
towards synchronizing

1449
00:55:56,770 --> 00:55:58,400
to the resonant mode
of the structure.

1450
00:55:58,400 --> 00:56:00,800
And this is part of, like,
how birds fly

1451
00:56:00,800 --> 00:56:04,300
at a fraction of the energetics

1452
00:56:04,300 --> 00:56:05,800
of our airplanes, right.

1453
00:56:05,800 --> 00:56:09,270
Because they are working at
a coupled resonance

1454
00:56:09,270 --> 00:56:11,300
between the bird
and the local environments--

1455
00:56:11,300 --> 00:56:13,600
the bird's body and the local

1456
00:56:13,600 --> 00:56:15,430
aerodynamic environment
that it's in,

1457
00:56:15,430 --> 00:56:17,100
which is also influencing.

1458
00:56:17,100 --> 00:56:18,970
And so getting the ability to
figure out how to do that

1459
00:56:18,970 --> 00:56:20,500
coupling of the dynamics
from your--

1460
00:56:20,500 --> 00:56:22,130
all the way from
your control structure

1461
00:56:22,130 --> 00:56:23,800
through the body
to the local environment

1462
00:56:23,800 --> 00:56:25,470

and make that one coupled system

1463
00:56:25,470 --> 00:56:27,570
is, I think, the holy grail
of efficiency.

1464
00:56:27,570 --> 00:56:29,600
and I think this is, hopefully,
part of the solution

1465
00:56:29,600 --> 00:56:31,300
of getting there, right.

1466
00:56:31,300 --> 00:56:32,730
I can't claim
that I'm there yet,

1467
00:56:32,730 --> 00:56:34,600
but I think it's a direction
that will get us

1468
00:56:34,600 --> 00:56:36,000
to very high levels
of efficiency

1469
00:56:36,000 --> 00:56:38,230
Arguably, one little side
amusing point,

1470
00:56:38,230 --> 00:56:40,600
is that we should be able to
build a robotic horse

1471
00:56:40,600 --> 00:56:42,630
that we can run with
a one-horsepower motor, right?

1472
00:56:42,630 --> 00:56:44,770
So that just shows you how
inefficient--

1473
00:56:44,770 --> 00:56:46,800
[laughter]

1474
00:56:46,800 --> 00:56:49,830
That--that's how inefficient
our current approaches are.

1475
00:56:49,830 --> 00:56:51,900
All right.

1476
00:56:51,900 --> 00:56:54,730
Locomotion speed,

1477
00:56:54,730 --> 00:56:56,100
again, this is
a design principle.

1478
00:56:56,100 --> 00:56:58,000
I mean, SUPERball is gonna be
somewhat limited

1479
00:56:58,000 --> 00:56:59,570
in its top speeds.

1480
00:56:59,570 --> 00:57:01,870
In simulation, we had it going
really fast at times,

1481
00:57:01,870 --> 00:57:03,970
but it's--you know,
you're doing the sort of

1482
00:57:03,970 --> 00:57:05,470
dynamic flopping and rolling.

1483
00:57:05,470 --> 00:57:06,770
We haven't pushed it
to the point

1484
00:57:06,770 --> 00:57:09,430
of trying to get super,
you know, dynamic locomotions.

1485
00:57:09,430 --> 00:57:10,800
Again, in simulation we have,

1486
00:57:10,800 --> 00:57:13,200
and it looks nice
and fun and fast,

1487
00:57:13,200 --> 00:57:15,500
but we haven't built that yet
in hardware.

1488
00:57:15,500 --> 00:57:17,300
But again, it's a design
principle

1489
00:57:17,300 --> 00:57:19,300
so I don't think there's
any particular limitation

1490
00:57:19,300 --> 00:57:20,870
to its ultimate speed.

1491
00:57:20,870 --> 00:57:22,170
And then you would really
start--

1492
00:57:22,170 --> 00:57:23,530
if you really want to have
a fast-moving robot,

1493
00:57:23,530 --> 00:57:25,230
you start getting into
the biomechanical design of it,

1494

00:57:25,230 --> 00:57:26,630
right.

1495
00:57:26,630 --> 00:57:28,770
Are you gonna be using legs?
Are you gonna, you know--

1496
00:57:28,770 --> 00:57:30,870
What's the overall shape
of the robot gonna be,

1497
00:57:30,870 --> 00:57:33,230
and how are you generating
that power and force?

1498
00:57:33,230 --> 00:57:36,800
Stability of
the sensor platform.

1499
00:57:36,800 --> 00:57:38,370
Yes, so this is gonna be

1500
00:57:38,370 --> 00:57:39,830
one of the interesting
challenges, right.

1501
00:57:39,830 --> 00:57:41,830
Right now we have this concept
of putting a payload

1502
00:57:41,830 --> 00:57:45,070
in the centrally suspended
mechanism

1503
00:57:45,070 --> 00:57:46,300
in the middle of the robot,

1504
00:57:46,300 --> 00:57:47,670
and then you've got
this rolling robot,

1505
00:57:47,670 --> 00:57:49,500
and you're like, "Oh, my gosh,
I'm gonna get--

1506
00:57:49,500 --> 00:57:52,670
I'm gonna get really dizzy
trying to drive this thing."

1507
00:57:52,670 --> 00:57:55,900
And--but there are
a number of solutions

1508
00:57:55,900 --> 00:57:57,500
I can imagine
to that, right.

1509
00:57:57,500 --> 00:58:00,700
One idea is you have a number
of very small cameras

1510
00:58:00,700 --> 00:58:02,200
around that payload

1511
00:58:02,200 --> 00:58:04,370
and you can do a virtual
aperture, you know, algorithm.

1512
00:58:04,370 --> 00:58:06,430
This is stuff that's been done
many times

1513
00:58:06,430 --> 00:58:09,670
where you create a synthetic
single stable view

1514
00:58:09,670 --> 00:58:11,800
out of a bunch of
rolling moving cameras.

1515
00:58:11,800 --> 00:58:13,130
It's possible to do that, right?

1516
00:58:13,130 --> 00:58:16,000
There may be other solutions
for, how do you manage

1517
00:58:16,000 --> 00:58:19,530
the locomotion and navigation
of the system?

1518
00:58:19,530 --> 00:58:21,670
And again, you know,

1519
00:58:21,670 --> 00:58:23,270
there may be other approaches
that we--

1520
00:58:23,270 --> 00:58:25,270
we end up coming up with
eventually

1521
00:58:25,270 --> 00:58:27,500
that will give us the--
sort of the ultimate

1522
00:58:27,500 --> 00:58:30,370
perfect hybrid, right.

1523
00:58:30,370 --> 00:58:32,570
You know, one--one--one thing
that we have to remember

1524
00:58:32,570 --> 00:58:34,770
is that when you're building
an actual space system,

1525
00:58:34,770 --> 00:58:37,770
you are always trading off

different requirements,

1526
00:58:37,770 --> 00:58:39,670
different optimizations
against each other, right.

1527
00:58:39,670 --> 00:58:42,370
So we may be losing

1528
00:58:42,370 --> 00:58:44,900
certain forms of stability
and management

1529
00:58:44,900 --> 00:58:46,670
in the locomotion,

1530
00:58:46,670 --> 00:58:48,600
but gaining this great ability

1531
00:58:48,600 --> 00:58:50,370
to be robust to falls and slips

1532
00:58:50,370 --> 00:58:53,130
and to be able to survive
a landing without an air bag,

1533
00:58:53,130 --> 00:58:55,770
and so you may trade off some of
these, you know, capabilities,

1534
00:58:55,770 --> 00:58:57,400
one for the other, to enable
sort of the--

1535
00:58:57,400 --> 00:58:59,400
the perfect mission design.

1536
00:58:59,400 --> 00:59:01,870
So these are all areas, though,

that we're very interested

1537
00:59:01,870 --> 00:59:03,330
in continuing to--
to think about,

1538
00:59:03,330 --> 00:59:04,930
and I just haven't had
the opportunity

1539
00:59:04,930 --> 00:59:08,730
to really tackle head-on yet.

1540
00:59:08,730 --> 00:59:11,830
- Hi, thank you.
That was a great talk.

1541
00:59:11,830 --> 00:59:13,900
As a biologist who loves robots,

1542
00:59:13,900 --> 00:59:17,930
this is a fun interface to see
someone playing around in.

1543
00:59:17,930 --> 00:59:21,300
But I think you may have
probably already thought of this

1544
00:59:21,300 --> 00:59:23,330
considering
your closed loop thing

1545
00:59:23,330 --> 00:59:25,500
that you were
playing around with,

1546
00:59:25,500 --> 00:59:29,230
but the--there was
a C. elegans robot

1547
00:59:29,230 --> 00:59:31,700
that was made
and it responds--

1548
00:59:31,700 --> 00:59:35,230
a couple years ago
and it will respond by itself

1549
00:59:35,230 --> 00:59:38,130
to an obstacle, for example.

1550
00:59:38,130 --> 00:59:41,600
So it runs into--and C. elegans
has a stereotype behavior

1551
00:59:41,600 --> 00:59:44,170
to get around it eventually.

1552
00:59:44,170 --> 00:59:46,200
And I'm wondering,

1553
00:59:46,200 --> 00:59:49,630
because you may drop a robot
in an environment,

1554
00:59:49,630 --> 00:59:52,630
you may not know
what's there exactly.

1555
00:59:52,630 --> 00:59:54,530
Are you thinking about how you
can get this robot

1556
00:59:54,530 --> 00:59:59,270
to just respond to just
an obstacle, for example?

1557
00:59:59,270 --> 01:00:01,830
- Yeah, well, so in some of

the videos that you--I showed,

1558
01:00:01,830 --> 01:00:04,000
like, where it was going over
some of the lump--

1559
01:00:04,000 --> 01:00:06,500
like, the spine robot was going
over some of the lumpy ground

1560
01:00:06,500 --> 01:00:08,670
or some of the blocks
and things like that,

1561
01:00:08,670 --> 01:00:12,930
and even--I had one picture here

1562
01:00:12,930 --> 01:00:14,570
that was from some
very early research

1563
01:00:14,570 --> 01:00:17,930
when we were doing
the spine robots.

1564
01:00:17,930 --> 01:00:20,270
This one, right.

1565
01:00:20,270 --> 01:00:22,700
And--and where you see it going
across these various terrains

1566
01:00:22,700 --> 01:00:24,600
and the walls and whatnot,

1567
01:00:24,600 --> 01:00:26,400
that was all done with no
knowledge of the environment.

1568

01:00:26,400 --> 01:00:28,830
That was all done as--
as using the sort of

1569
01:00:28,830 --> 01:00:30,700
reactive distributive control
approach,

1570
01:00:30,700 --> 01:00:32,230
where it would just
run into these things

1571
01:00:32,230 --> 01:00:34,730
and sort of eventually
find its way over them.

1572
01:00:34,730 --> 01:00:37,770
So I think there is a lot that
can be done with that.

1573
01:00:37,770 --> 01:00:41,000
And you can imagine--
so, you know, it's...

1574
01:00:41,000 --> 01:00:42,370
[sighs]

1575
01:00:42,370 --> 01:00:44,730
We took--you know,
if you just use

1576
01:00:44,730 --> 01:00:46,200
your proprioceptive sensors,

1577
01:00:46,200 --> 01:00:48,630
your sense of touch and your
sense of feeling the forces

1578
01:00:48,630 --> 01:00:50,270
and the things you collide with,

1579
01:00:50,270 --> 01:00:51,970
you can figure out
all sorts of ways

1580
01:00:51,970 --> 01:00:54,430
to manage how to navigate
through very complex situations

1581
01:00:54,430 --> 01:00:56,130
I have a one-year-old son
at home

1582
01:00:56,130 --> 01:00:58,030
and he's learning to walk,
and, you know, he doesn't have

1583
01:00:58,030 --> 01:00:59,430
a very complex
planning algorithm.

1584
01:00:59,430 --> 01:01:01,530
He just kind of like
pushes and pushes

1585
01:01:01,530 --> 01:01:03,530
until he eventually, like,
crawls over my body

1586
01:01:03,530 --> 01:01:05,470
and, you know, and goes
wherever he's going, right.

1587
01:01:05,470 --> 01:01:08,370
And it works.
It gets you there.

1588
01:01:08,370 --> 01:01:11,100
The advantage of using things
like your eyes,

1589
01:01:11,100 --> 01:01:13,630
your other distance sensors,

1590
01:01:13,630 --> 01:01:16,170
allow you to do things
in a more efficient manner.

1591
01:01:16,170 --> 01:01:18,770
It really optimizes
how you spend your energy.

1592
01:01:18,770 --> 01:01:21,970
Now, you can, instead of, like,
bumping into this and--

1593
01:01:21,970 --> 01:01:23,800
and getting around it
eventually,

1594
01:01:23,800 --> 01:01:25,130
you're like, "Oh, yeah,

1595
01:01:25,130 --> 01:01:26,470
I could just, you know,
walk around that."

1596
01:01:26,470 --> 01:01:28,200
That'd be real easy, right.

1597
01:01:28,200 --> 01:01:29,600
So you do your own motion
planning

1598
01:01:29,600 --> 01:01:31,100
and it's--it's more
energy efficient

1599
01:01:31,100 --> 01:01:33,570

and nicer on the skin, too.

1600
01:01:33,570 --> 01:01:35,300
So--so it's all about what level
of capability

1601
01:01:35,300 --> 01:01:36,800
you want to get to.

1602
01:01:36,800 --> 01:01:38,700
But I think
the important thing is

1603
01:01:38,700 --> 01:01:40,230
that a lot of
traditional robotics

1604
01:01:40,230 --> 01:01:43,470
has started coming out of, like,
a very industrial environment,

1605
01:01:43,470 --> 01:01:45,770
where you're like,
I need to perfectly plan

1606
01:01:45,770 --> 01:01:47,670
every single thing I do,

1607
01:01:47,670 --> 01:01:49,900
and--and have that control
from the top end.

1608
01:01:49,900 --> 01:01:51,570
We think about our tasks.

1609
01:01:51,570 --> 01:01:53,700
This is what we are mentally
aware of are all the tasks

1610

01:01:53,700 --> 01:01:55,070
that we want to accomplish,

1611
01:01:55,070 --> 01:01:56,930
and so we've designed robots
to do things that way.

1612
01:01:56,930 --> 01:02:00,000
I think it's very important to
actually throw that all away

1613
01:02:00,000 --> 01:02:03,070
for a moment,
start from the bottom up.

1614
01:02:03,070 --> 01:02:06,500
Figure out, how do you make
a system that is so capable

1615
01:02:06,500 --> 01:02:07,900
and robust of interacting
with the environment

1616
01:02:07,900 --> 01:02:09,630
that you can do this,
that you can bump into stuff

1617
01:02:09,630 --> 01:02:12,770
and eventually find your way
around it without breaking.

1618
01:02:12,770 --> 01:02:14,000
Have that as your foundation.

1619
01:02:14,000 --> 01:02:16,200
And now on top of
that foundation,

1620
01:02:16,200 --> 01:02:18,170
you start figuring out how to

take that capability

1621
01:02:18,170 --> 01:02:20,130
and plan for it and control it

1622
01:02:20,130 --> 01:02:22,930
through a more complex, planned,
intentional movement.

1623
01:02:22,930 --> 01:02:26,330
And that's really gonna be where
you get the optimal balance

1624
01:02:26,330 --> 01:02:28,130
of capabilities.

1625
01:02:28,130 --> 01:02:30,500
But it means taking kind of
a couple steps backwards,

1626
01:02:30,500 --> 01:02:32,800
relative to state-of-the-art
robotics,

1627
01:02:32,800 --> 01:02:36,300
in order to make
the big leap forward.

1628
01:02:36,300 --> 01:02:38,770
- So please join me
in thanking Vytas

1629
01:02:38,770 --> 01:02:40,300
for an excellent seminar.

1630
01:02:40,300 --> 01:02:41,400
[applause]

1631
01:02:41,400 --> 01:02:43,500

Thank you very much.