1
00:00:01,000 --> 00:00:07,000
[music playing]

2
00:00:17,033 --> 00:00:21,300
- Welcome to the 2015
NASA Ames Summer Series.

3
00:00:22,733 --> 00:00:26,733
Modular design reduces risk
and speeds up

4
00:00:26,733 --> 00:00:28,966
technology advancements.

5
00:00:30,333 --> 00:00:35,100
Also, combining capabilities
from different fields

6
00:00:35,100 --> 00:00:38,400
leads to disruptive evolution
of technology.

7
00:00:39,900 --> 00:00:42,700
So the combination
of modular design

8
00:00:42,700 --> 00:00:45,266
and looking at different fields
in combination

9
00:00:45,266 --> 00:00:50,366
really advances whatever
technology we're looking at.

10
00:00:50,366 --> 00:00:53,600
Today's talk,
entitled "Affordable Airplanes:

11
00:00:53,600 --> 00:00:57,766

Modular Design
and Additive Manufacturing,"

12
00:00:57,766 --> 00:01:00,500
will be given
by Kevin Reynolds.

13
00:01:00,500 --> 00:01:03,000
Kevin received
dual bachelor's degrees

14
00:01:03,000 --> 00:01:05,833
in physics and mathematics
with a minor

15
00:01:05,833 --> 00:01:09,933
in electronics
from Norfolk State University

16
00:01:09,933 --> 00:01:12,500
and then went on
to get the master's degree,

17
00:01:12,500 --> 00:01:15,966
and as you could guess,
he did a dual master's degree

18
00:01:15,966 --> 00:01:18,366
in aeronautics
and mechanical engineering

19
00:01:18,366 --> 00:01:20,066
from Stanford.

20
00:01:20,066 --> 00:01:24,000
He's both an NSF and a Stanford
Graduate School of Business

21
00:01:24,000 --> 00:01:27,433
Insight program fellow.

22
00:01:27,433 --> 00:01:31,500
Along the way,
he has had many experiences.

23
00:01:31,500 --> 00:01:33,800
He's worked
at CERN in Switzerland,

24
00:01:33,800 --> 00:01:36,433
BMW Technology in Germany,

25
00:01:36,433 --> 00:01:38,533
Hitachi in Japan,

26
00:01:38,533 --> 00:01:41,033
and Golden Key International
in China.

27
00:01:45,600 --> 00:01:49,000
He came to NASA Ames
in 2010 and--

28
00:01:49,000 --> 00:01:52,000
as a civil servant to the--

29
00:01:52,000 --> 00:01:53,766
as an aerospace engineer

30
00:01:53,766 --> 00:01:56,500
in the Intelligent System
Division.

31
00:01:58,666 --> 00:02:02,333
He has won numerous awards,
and obviously,

32
00:02:02,333 --> 00:02:05,533
he has won the NASA Ames

33
00:02:05,533 --> 00:02:07,633
that my office handles.

34
00:02:07,633 --> 00:02:10,866
So please join me
in welcoming Kevin Reynolds.

35
00:02:10,866 --> 00:02:14,366
[applause]

36
00:02:14,366 --> 00:02:15,800
- Thank you.

37
00:02:19,100 --> 00:02:21,766
Thank you.
Thank you for the introduction.

38
00:02:21,766 --> 00:02:25,133
And it's a pleasure for me
to have the opportunity today

39
00:02:25,133 --> 00:02:26,266
to present to you on a topic

40
00:02:26,266 --> 00:02:28,266
that I find
extremely fascinating

41
00:02:28,266 --> 00:02:31,466
and that is of using
3-D printing to make airplanes.

42
00:02:31,466 --> 00:02:34,733
So, as you can see, the title is
"Affordable Airplanes:

43
00:02:34,733 --> 00:02:37,433

Modular Design
and Additive Manufacturing."

44
00:02:37,433 --> 00:02:40,833
I want to start just by focusing
on the word "affordable"

45
00:02:40,833 --> 00:02:44,600
because it's somewhat misleading
in that everyone has

46
00:02:44,600 --> 00:02:46,600
their own perception
of what is affordable,

47
00:02:46,600 --> 00:02:51,200
and that perception changes
as we go through our lifetime.

48
00:02:51,200 --> 00:02:53,633
So instead of this talk
focusing on actually placing

49
00:02:53,633 --> 00:02:57,433
a value--a dollar value--
on affordable airplanes,

50
00:02:57,433 --> 00:03:00,200
we're really going to focus on
the value proposition

51
00:03:00,200 --> 00:03:03,366
that can be offered
by two key design elements.

52
00:03:03,366 --> 00:03:05,466
And those elements
are modular design

53
00:03:05,466 --> 00:03:09,133

and additive manufacturing,
also known as 3-D printing.

54
00:03:09,133 --> 00:03:12,566
This talk is focused on
demonstrating the use

55
00:03:12,566 --> 00:03:15,133
of those design elements
for unmanned aircraft

56
00:03:15,133 --> 00:03:18,566
but may have future applications
for other type of airplanes

57
00:03:18,566 --> 00:03:21,966
that are designed
to different requirements.

58
00:03:21,966 --> 00:03:23,633
I want to also acknowledge

59
00:03:23,633 --> 00:03:26,300
and thank the contributors
of this work.

60
00:03:26,300 --> 00:03:28,133
The success of the project
was built

61
00:03:28,133 --> 00:03:30,266
on the shoulders of giants,
as they say,

62
00:03:30,266 --> 00:03:34,266
and so credit is given to
the team that made this happen

63
00:03:34,266 --> 00:03:37,100
as well as the advisors

and the mentors

64
00:03:37,100 --> 00:03:40,666
that indirectly or directly
influenced the work here:

65
00:03:40,666 --> 00:03:45,466
Matt Fladeland, Dr. Don Nguyen,
Dr. Bob Dahlgren, and others.

66
00:03:45,466 --> 00:03:48,100
Many others.

67
00:03:48,100 --> 00:03:51,900
So I wanted to start
by framing the talk

68
00:03:51,900 --> 00:03:55,466
with an experience
that I had as an early engineer.

69
00:03:55,466 --> 00:03:58,100
In fact, I was actually
a physics major at the time,

70
00:03:58,100 --> 00:04:02,966
and I visited a place called
the Pima Air & Space Museum.

71
00:04:02,966 --> 00:04:04,833
This place is
in the middle of the desert

72
00:04:04,833 --> 00:04:06,700
in a place
called Tucson, Arizona,

73
00:04:06,700 --> 00:04:10,400
and this is where
airplanes go to die.

74
00:04:10,400 --> 00:04:13,766
So, at the end of a lifetime,
which is usually determined

75
00:04:13,766 --> 00:04:16,300
by when the materials
in the aircraft

76
00:04:16,300 --> 00:04:17,700
have reached the fatigue point

77
00:04:17,700 --> 00:04:20,266
where they're no longer
deemed airworthy,

78
00:04:20,266 --> 00:04:21,900
they are taken to this place,

79
00:04:21,900 --> 00:04:25,266
and the low humidity
in the desert

80
00:04:25,266 --> 00:04:27,933
preserves the parts
so that it can then

81
00:04:27,933 --> 00:04:31,300
perhaps be reused
in certain applications.

82
00:04:31,300 --> 00:04:33,266
But here in the middle
of the desert,

83
00:04:33,266 --> 00:04:36,033
there are over 4,000 airplanes
that are just sitting,

84

00:04:36,033 --> 00:04:38,866
waiting for the possibility
of having a part

85
00:04:38,866 --> 00:04:40,833
here or there salvaged
or repurposed

86
00:04:40,833 --> 00:04:42,466
for a new airplane.

87
00:04:42,466 --> 00:04:43,800
The engines, obviously,

88
00:04:43,800 --> 00:04:47,300
are usually taken off first
and overhauled,

89
00:04:47,300 --> 00:04:49,033
but this really points
to a big problem

90
00:04:49,033 --> 00:04:51,100
that the aerospace industry
is facing,

91
00:04:51,100 --> 00:04:54,033
and that is:
how can we extend

92
00:04:54,033 --> 00:04:57,666
the useful lifetime of aircraft
so that--

93
00:04:57,666 --> 00:05:02,033
by reusing parts,
by taking surplus parts,

94
00:05:02,033 --> 00:05:03,400
and repurposing them

95
00:05:03,400 --> 00:05:05,566
so that we don't have
all this waste?

96
00:05:05,566 --> 00:05:08,866
Because this was
my first experience

97
00:05:08,866 --> 00:05:11,100
when I was an undergraduate
visiting this place.

98
00:05:11,100 --> 00:05:14,133
But 15 years later,
I think of this place,

99
00:05:14,133 --> 00:05:15,233
and I think,
this is the worst place

100
00:05:15,233 --> 00:05:16,800
in the world
for an aerospace engineer,

101
00:05:16,800 --> 00:05:19,000
because who wants to design
an airplane

102
00:05:19,000 --> 00:05:22,833
that will sit in the desert
for 20 years?

103
00:05:22,833 --> 00:05:26,166
Well, design an airplane
and then have that airplane

104
00:05:26,166 --> 00:05:27,966
sit in the middle of the desert.

105
00:05:27,966 --> 00:05:30,066
And so this is really
what helped to frame

106
00:05:30,066 --> 00:05:32,300
the rest of the discussion
today.

107
00:05:32,300 --> 00:05:35,200
So I look for places
for inspiration

108
00:05:35,200 --> 00:05:38,066
in many different places,
but one of the unlikely places

109
00:05:38,066 --> 00:05:39,833
that I found the inspiration

110
00:05:39,833 --> 00:05:41,700
was actually
my four-year-old son.

111
00:05:41,700 --> 00:05:45,666
His name is Arlo,
and he aspires one day

112
00:05:45,666 --> 00:05:49,900
to be an astronaut,
and he loves playing with LEGOs.

113
00:05:49,900 --> 00:05:53,266
And most of us are familiar
with LEGO design,

114
00:05:53,266 --> 00:05:54,933
but the idea of LEGO design

115
00:05:54,933 --> 00:05:56,333

is that you can take
very simple components

116
00:05:56,333 --> 00:05:58,066
and rearrange them
and reorient them

117
00:05:58,066 --> 00:05:59,900
in ways that will produce
a new product.

118
00:05:59,900 --> 00:06:01,633
Sometimes that product
can be bigger

119
00:06:01,633 --> 00:06:04,566
than the person
actually creating it.

120
00:06:04,566 --> 00:06:07,066
To the right,
he is using his imagination

121
00:06:07,066 --> 00:06:10,733
to show what he would look like
as an astronaut.

122
00:06:10,733 --> 00:06:14,533
So this really
encouraged me to think,

123
00:06:14,533 --> 00:06:18,733
are there things that I can do
to possibly optimize

124
00:06:18,733 --> 00:06:21,133
a process for making an airplane
so that we can extend

125
00:06:21,133 --> 00:06:23,833

the useful life of that airplane
and make it--

126
00:06:23,833 --> 00:06:28,166
and reduce the waste
associated with these airplanes?

127
00:06:28,166 --> 00:06:29,966
So one other process--

128
00:06:29,966 --> 00:06:31,400
processes that I want
to focus on

129
00:06:31,400 --> 00:06:34,100
is that
of additive manufacturing,

130
00:06:34,100 --> 00:06:35,766
also known as 3-D printing,
and the process

131
00:06:35,766 --> 00:06:39,200
of 3-D printing is that
you can take a CAD drawing--

132
00:06:39,200 --> 00:06:42,033
a virtual shape--
and you can create

133
00:06:42,033 --> 00:06:46,766
a three-dimensional object
by depositing layers

134
00:06:46,766 --> 00:06:48,800
on top of one another,
and the different methods

135
00:06:48,800 --> 00:06:52,866
that are used differentiate

136
00:06:52,866 --> 00:06:55,266
between the different types of
printers used for this method.

137
00:06:55,266 --> 00:06:56,733
We want to leverage this
in some way

138
00:06:56,733 --> 00:07:01,700
in order to repurpose
some of the existing parts

139
00:07:01,700 --> 00:07:03,533
of these airplanes.

140
00:07:03,533 --> 00:07:08,200
So the innovation
lies in the idea that,

141
00:07:08,200 --> 00:07:10,566
from an amorphous design space,

142
00:07:10,566 --> 00:07:12,366
we can then start
creating designs

143
00:07:12,366 --> 00:07:13,866
that are optimized specifically

144
00:07:13,866 --> 00:07:15,366
for meeting
mission requirements,

145
00:07:15,366 --> 00:07:16,666
and the two fundamental elements

146
00:07:16,666 --> 00:07:19,533
are the modular design

and additive manufacturing.

147
00:07:19,533 --> 00:07:23,400
The advantage of modular design
is that we intentionally design

148
00:07:23,400 --> 00:07:27,500
an airplane so that
the parts can be interchanged

149
00:07:27,500 --> 00:07:30,700
and we can update the design
as the technology matures

150
00:07:30,700 --> 00:07:33,100
and as it advances.

151
00:07:33,100 --> 00:07:35,000
The main advantages
of additive manufacturing

152
00:07:35,000 --> 00:07:38,200
are that you can print
and realize a part on demand

153
00:07:38,200 --> 00:07:40,066
without having to wait
for something

154
00:07:40,066 --> 00:07:41,466
to be shipped to you.

155
00:07:41,466 --> 00:07:45,500
And this can have huge impact
on mission requirements

156
00:07:45,500 --> 00:07:50,566
that may be in remote locations
and other specific situations

157
00:07:50,566 --> 00:07:51,700
such as that.

158
00:07:51,700 --> 00:07:54,333
But the real advantage
is in reducing

159
00:07:54,333 --> 00:07:56,733
the development time,
which can then translate

160
00:07:56,733 --> 00:07:59,366
into development cost

161
00:07:59,366 --> 00:08:02,566
for the specific application.

162
00:08:02,566 --> 00:08:06,666
So high-performance airplanes
represent a big opportunity

163
00:08:06,666 --> 00:08:08,900
for reducing overall cost.

164
00:08:08,900 --> 00:08:10,900
You can think
of the vertical axis

165
00:08:10,900 --> 00:08:12,866
being the sticker price
of an airplane.

166
00:08:12,866 --> 00:08:14,933
We also call it
the acquisition cost.

167
00:08:14,933 --> 00:08:17,466
And traditionally,
that acquisition cost

168
00:08:17,466 --> 00:08:21,000
is a function
of how high performing

169
00:08:21,000 --> 00:08:23,366
the airplane is,
and we usually--

170
00:08:23,366 --> 00:08:25,733
we tend to use a metric
called endurance

171
00:08:25,733 --> 00:08:29,433
to describe the performance
of an unmanned vehicle

172
00:08:29,433 --> 00:08:31,066
that could be used
for a NASA mission.

173
00:08:31,066 --> 00:08:35,000
So the longer time
that airplane can fly--

174
00:08:35,000 --> 00:08:37,166
and usually,
the bigger the airplane is,

175
00:08:37,166 --> 00:08:39,166
the higher the acquisition cost.

176
00:08:39,166 --> 00:08:40,433
But what we really want
to focus on

177
00:08:40,433 --> 00:08:43,866
is how to make this relationship
more or less linear,

178
00:08:43,866 --> 00:08:48,733
as opposed to exponential,
as we see in the plot.

179
00:08:48,733 --> 00:08:53,066
So we want to illustrate
some of the concepts--

180
00:08:53,066 --> 00:08:56,166
specifically of modular design
and additive manufacturing,

181
00:08:56,166 --> 00:08:58,766
using an existing design
that many of you

182
00:08:58,766 --> 00:09:02,200
have seen on the way in
called the FrankenEye design,

183
00:09:02,200 --> 00:09:05,966
and we want to also extract
potential lessons learned

184
00:09:05,966 --> 00:09:07,633
for future applications.

185
00:09:07,633 --> 00:09:09,533
So we've talked a little bit
about the motivation,

186
00:09:09,533 --> 00:09:13,266
so let's dive
into the modular design aspect.

187
00:09:13,266 --> 00:09:15,066
So Earth Science Missions
here at NASA

188

00:09:15,066 --> 00:09:18,233
are really a core competency
that we have

189
00:09:18,233 --> 00:09:21,266
relative to other NASA centers,
and Earth Science Missions

190
00:09:21,266 --> 00:09:24,200
really focused
on taking unmanned aircraft,

191
00:09:24,200 --> 00:09:26,200
or even manned aircraft,
and flying them

192
00:09:26,200 --> 00:09:28,400
to parts of the world that
we want to better understand.

193
00:09:28,400 --> 00:09:31,300
And one of the places that
we want to better understand

194
00:09:31,300 --> 00:09:32,433
are volcanoes.

195
00:09:32,433 --> 00:09:33,933
This is a picture
that was taken

196
00:09:33,933 --> 00:09:37,166
from Turrialba Volcano in 2003,

197
00:09:37,166 --> 00:09:40,733
which is located in Costa Rica,
and the scientists

198
00:09:40,733 --> 00:09:42,766
were very interested

in understanding

199
00:09:42,766 --> 00:09:45,333
what type of gasses
were being emitted

200
00:09:45,333 --> 00:09:47,500
from the volcano
and how that might impact

201
00:09:47,500 --> 00:09:49,233
climate change, for instance.

202
00:09:49,233 --> 00:09:51,133
But what we found out
very quickly

203
00:09:51,133 --> 00:09:54,066
was that, when we took parts
that were surplus from--

204
00:09:54,066 --> 00:09:56,300
as military hardware,

205
00:09:56,300 --> 00:09:59,900
those airplanes were not
optimized for the long endurance

206
00:09:59,900 --> 00:10:02,000
that we wanted
in our science missions.

207
00:10:02,000 --> 00:10:04,400
Science missions also tend
to want aircraft

208
00:10:04,400 --> 00:10:07,066
that will carry large payloads,
large sensors,

209
00:10:07,066 --> 00:10:09,366
and fly those sensors
for long periods of time.

210
00:10:09,366 --> 00:10:11,366
We didn't have that
in the current design.

211
00:10:11,366 --> 00:10:13,666
So this raises the question:
how can we optimize?

212
00:10:13,666 --> 00:10:16,666
How can we modify
an existing design

213
00:10:16,666 --> 00:10:18,933
so that we can meet
the performance requirements

214
00:10:18,933 --> 00:10:20,866
for the specific mission?

215
00:10:20,866 --> 00:10:22,566
So one of the ways
that we wanted

216
00:10:22,566 --> 00:10:25,800
to leverage technology
was through the use

217
00:10:25,800 --> 00:10:29,666
of additive manufacturing,
and this illustration

218
00:10:29,666 --> 00:10:32,333
compares the subtractive
manufacturing process

219

00:10:32,333 --> 00:10:34,033
to the additive
manufacturing process.

220
00:10:34,033 --> 00:10:36,400
Typically, in a subtractive
manufacturing process,

221
00:10:36,400 --> 00:10:37,966
you start with the material,

222
00:10:37,966 --> 00:10:40,100
and your design
is largely constrained

223
00:10:40,100 --> 00:10:42,366
by what you can manufacture
with that material.

224
00:10:42,366 --> 00:10:44,033
Carbon fiber, for instance,

225
00:10:44,033 --> 00:10:48,766
needs an autoclave
to solidify the part.

226
00:10:48,766 --> 00:10:51,100
And so, because of those type
of limitations,

227
00:10:51,100 --> 00:10:54,266
we also are limited
in terms of the final assembly

228
00:10:54,266 --> 00:10:56,700
that we hope to achieve.

229
00:10:56,700 --> 00:10:58,400
Additive manufacturing,
on the other end,

230
00:10:58,400 --> 00:11:01,966
really allows you
at the very early stages

231
00:11:01,966 --> 00:11:05,033
of the design
to focus on the functionality

232
00:11:05,033 --> 00:11:08,566
without being limited
directly by the material choice.

233
00:11:08,566 --> 00:11:12,200
And so we can generate parts

234
00:11:12,200 --> 00:11:13,566
that can then be sent
to a printer,

235
00:11:13,566 --> 00:11:16,333
and we can decide
on the materials

236
00:11:16,333 --> 00:11:20,166
based on the requirements
that we have.

237
00:11:20,166 --> 00:11:23,166
So, for this project,
we wanted to take advantage

238
00:11:23,166 --> 00:11:26,900
of the fact
that we had a good number

239
00:11:26,900 --> 00:11:29,766
of surplus UAVs
that had been provided to us

240
00:11:29,766 --> 00:11:32,266
by the U.S. Marines.

241
00:11:32,266 --> 00:11:33,933
And we--

242
00:11:33,933 --> 00:11:37,333
The feedstock that we had
for this specific project

243
00:11:37,333 --> 00:11:41,966
was the DragonEye UAV,
which is also here with me.

244
00:11:41,966 --> 00:11:44,933
This aircraft is designed
in five pieces,

245
00:11:44,933 --> 00:11:50,233
and those five pieces can be
detached from the aircraft,

246
00:11:50,233 --> 00:11:52,533
so you can simply
snap the wings off,

247
00:11:52,533 --> 00:11:55,233
which are being held together
using bungee cords.

248
00:11:55,233 --> 00:11:56,733
And this is really nice,

249
00:11:56,733 --> 00:12:00,500
because if you hit a tree
or if you hit the ground

250
00:12:00,500 --> 00:12:03,766
or you hit something else,

then you can absorb the energy

251
00:12:03,766 --> 00:12:06,666
in the joint instead of
having it break apart.

252
00:12:06,666 --> 00:12:09,066
That would need to be repaired.

253
00:12:11,300 --> 00:12:12,866
So, because of the design
of this airplane,

254
00:12:12,866 --> 00:12:16,266
we wanted to leverage the fact
that we had a modular wing,

255
00:12:16,266 --> 00:12:18,300
we had
a modular payload compartment,

256
00:12:18,300 --> 00:12:20,800
which tends to be the nose cone.

257
00:12:20,800 --> 00:12:22,066
And we wanted
to build off of that

258
00:12:22,066 --> 00:12:25,333
by using 3-D printing
to create new parts

259
00:12:25,333 --> 00:12:27,366
that would enhance
the performance

260
00:12:27,366 --> 00:12:30,566
of the existing design.

261

00:12:30,566 --> 00:12:33,333
So the five parts
are shown here.

262
00:12:33,333 --> 00:12:36,500
The two wing modules
and a center wing pod

263
00:12:36,500 --> 00:12:39,600
that holds the battery
and then the tail and the nose

264
00:12:39,600 --> 00:12:41,633
are those components.

265
00:12:41,633 --> 00:12:44,866
And this design is such
that it can be assembled

266
00:12:44,866 --> 00:12:46,800
in less than five minutes
for the purposes

267
00:12:46,800 --> 00:12:50,533
of a typical mission.

268
00:12:50,533 --> 00:12:55,033
So, to demonstrate this concept,
we took several DragonEye UAVs

269
00:12:55,033 --> 00:12:57,400
and the components
that they consisted of

270
00:12:57,400 --> 00:12:59,400
and we looked at ways
of rearranging them

271
00:12:59,400 --> 00:13:01,600
or reorienting them

in a way that would improve

272
00:13:01,600 --> 00:13:02,766
performance.

273
00:13:02,766 --> 00:13:04,933
In general, a long, slender wing
will provide

274
00:13:04,933 --> 00:13:07,800
the longest endurance
for an aircraft.

275
00:13:07,800 --> 00:13:11,000
And so this is an example
of an aircraft

276
00:13:11,000 --> 00:13:13,866
where we attempted to print
essentially every part

277
00:13:13,866 --> 00:13:17,033
of the aircraft,
including the wing sections,

278
00:13:17,033 --> 00:13:18,733
the structural components
as well,

279
00:13:18,733 --> 00:13:20,700
the nose cones,
and propeller blades.

280
00:13:20,700 --> 00:13:22,666
And this is just
to demonstrate

281
00:13:22,666 --> 00:13:25,300
the vast variety of parts
that we could achieve

282
00:13:25,300 --> 00:13:31,200
using 3-D printing with, really,
there being limited

283
00:13:31,200 --> 00:13:36,166
material constraints
for producing a given part.

284
00:13:36,166 --> 00:13:37,600
And so you can think
of this design

285
00:13:37,600 --> 00:13:40,900
as being a function
of how many units

286
00:13:40,900 --> 00:13:42,466
are attached together.

287
00:13:42,466 --> 00:13:46,966
And so you can think of this
as being a 3U design,

288
00:13:46,966 --> 00:13:49,100
similar to the jargon
that's used

289
00:13:49,100 --> 00:13:51,333
in small satellite design.

290
00:13:51,333 --> 00:13:54,066
And so what we really want
in the Earth Science community

291
00:13:54,066 --> 00:13:56,566
is something that looks
like this.

292

00:13:56,566 --> 00:13:58,600
This is the Helios Aircraft,
which was actually

293
00:13:58,600 --> 00:14:00,166
a joint project between NASA

294
00:14:00,166 --> 00:14:02,333
and several other
government agencies,

295
00:14:02,333 --> 00:14:05,066
but it was an extremely
high-performance aircraft.

296
00:14:07,133 --> 00:14:09,000
The caveat, though,
was that this airplane

297
00:14:09,000 --> 00:14:10,866
wasn't designed for cost.

298
00:14:10,866 --> 00:14:13,866
And so
could we replicate something

299
00:14:13,866 --> 00:14:18,966
with a similar performance
but with a lower cost-point?

300
00:14:18,966 --> 00:14:21,833
So, as some of you may know,

301
00:14:21,833 --> 00:14:24,600
the Helios did crash
a few years back,

302
00:14:24,600 --> 00:14:28,266
and it was attributed
to some difficulties managing

303
00:14:28,266 --> 00:14:31,100
the flexibility of the wing
associated with the Helios

304
00:14:31,100 --> 00:14:32,933
and how that flexibility
was accounted for

305
00:14:32,933 --> 00:14:34,333
in the control system.

306
00:14:34,333 --> 00:14:36,366
Now we have tools
that allow us

307
00:14:36,366 --> 00:14:39,866
to model the flexibility
of the materials

308
00:14:39,866 --> 00:14:43,166
as well as the contributions
of the propulsion to the design.

309
00:14:43,166 --> 00:14:44,300
And so, going forward,

310
00:14:44,300 --> 00:14:45,966
we can look at designs
like this.

311
00:14:45,966 --> 00:14:48,666
This is a 16U design,

312
00:14:48,666 --> 00:14:51,633
which we have the capability
to model.

313
00:14:51,633 --> 00:14:54,466

So when you actually look
at the performance contributions

314
00:14:54,466 --> 00:14:55,866
of these individual elements,

315
00:14:55,866 --> 00:14:57,533
you can then start to understand

316
00:14:57,533 --> 00:14:59,533
how each component
is contributing

317
00:14:59,533 --> 00:15:01,433
to the overall performance.

318
00:15:01,433 --> 00:15:04,800
And normally,
when we use endurance

319
00:15:04,800 --> 00:15:07,800
as the metric for performance,
we can look

320
00:15:07,800 --> 00:15:10,933
at aerodynamic efficiency,
propulsive efficiency,

321
00:15:10,933 --> 00:15:12,600
and structural efficiency.

322
00:15:12,600 --> 00:15:15,233
This focus is really on
the propulsive efficiency

323
00:15:15,233 --> 00:15:17,400
and the aerodynamic efficiency
of the design

324

00:15:17,400 --> 00:15:19,200
and the different
contributions.

325
00:15:19,200 --> 00:15:21,700
In general,
when you take a propeller

326
00:15:21,700 --> 00:15:24,533
and you have it
blow across a wing,

327
00:15:24,533 --> 00:15:26,333
it enhances the dynamic--

328
00:15:26,333 --> 00:15:28,666
it increases
the dynamic pressure on the wing

329
00:15:28,666 --> 00:15:32,100
and thereby increases
the lift capacity of the wing.

330
00:15:32,100 --> 00:15:35,933
But the trade is that
it also contributes to drag.

331
00:15:35,933 --> 00:15:38,166
So, by making
these important trades

332
00:15:38,166 --> 00:15:40,066
and choosing
an optimal wingspan,

333
00:15:40,066 --> 00:15:42,966
we can establish the trade
between aerodynamic efficiency

334
00:15:42,966 --> 00:15:44,533

and propulsive efficiency,
which

335
00:15:44,533 --> 00:15:46,200
both feed into endurance,

336
00:15:46,200 --> 00:15:48,533
which is what
we're interested in.

337
00:15:48,533 --> 00:15:50,500
So say we wanted
to design an airplane

338
00:15:50,500 --> 00:15:52,966
that was optimized
for a specific mission,

339
00:15:52,966 --> 00:15:55,633
so we could choose
certain parameters,

340
00:15:55,633 --> 00:15:57,766
which we choose to optimize for.

341
00:15:57,766 --> 00:16:00,166
Maybe in this case,
it would be maximum range

342
00:16:00,166 --> 00:16:03,000
and other--
with other constraints

343
00:16:03,000 --> 00:16:04,833
on climb rate and other things.

344
00:16:04,833 --> 00:16:07,133
And then we can start
to generate trajectories

345
00:16:07,133 --> 00:16:11,166
that look something like this,
where we're looking at--

346
00:16:11,166 --> 00:16:13,666
the blue line represents
the trajectory that the aircraft

347
00:16:13,666 --> 00:16:17,600
would take from the--
in the vertical plane.

348
00:16:17,600 --> 00:16:20,833
And the green line
represents the speed

349
00:16:20,833 --> 00:16:22,500
at which that airplane
would fly.

350
00:16:22,500 --> 00:16:24,166
And so one thing
that we understand

351
00:16:24,166 --> 00:16:26,033
very quickly,
specifically with this

352
00:16:26,033 --> 00:16:29,700
battery-powered design,
is that speed-optimal flight

353
00:16:29,700 --> 00:16:32,433
is extremely important,
because it's a hit or a miss

354
00:16:32,433 --> 00:16:35,766
on the aerodynamic efficiency
of the design.

355
00:16:35,766 --> 00:16:37,666
And so this is just
an example of how,

356
00:16:37,666 --> 00:16:40,000
by understanding
how those different parameters

357
00:16:40,000 --> 00:16:42,666
feed into the mission,
you can then start to

358
00:16:42,666 --> 00:16:45,333
optimize for things
like maximum energy recovery

359
00:16:45,333 --> 00:16:48,500
in the descent
of the aircraft.

360
00:16:50,066 --> 00:16:52,000
So we talked a bit
about modular design.

361
00:16:52,000 --> 00:16:54,266
Now we want to talk more
about additive manufacturing

362
00:16:54,266 --> 00:16:56,733
and the contributions
it can potentially make

363
00:16:56,733 --> 00:17:01,666
to the structural efficiency
of a design.

364
00:17:01,666 --> 00:17:04,766
So this is a drawing
that was taken of the first

365
00:17:04,766 --> 00:17:08,766
powered flight here in the U.S.
by the Wright brothers.

366
00:17:08,766 --> 00:17:10,900
And the unusual thing
about this design

367
00:17:10,900 --> 00:17:12,566
was that it wasn't--

368
00:17:12,566 --> 00:17:14,866
it didn't come together
with aerospace-grade materials.

369
00:17:14,866 --> 00:17:18,033
It actually came together
with wires, cloth, and wood--

370
00:17:18,033 --> 00:17:19,766
things that you typically
wouldn't think

371
00:17:19,766 --> 00:17:21,600
go inside of an airplane.

372
00:17:21,600 --> 00:17:23,066
But one of the things

373
00:17:23,066 --> 00:17:24,400
that we know
that they understood

374
00:17:24,400 --> 00:17:26,533
was how to make
lightweight structures

375
00:17:26,533 --> 00:17:28,833
using those materials,

and they had to overcome

376
00:17:28,833 --> 00:17:31,533
the challenges of the propulsion
and of the aerodynamics

377
00:17:31,533 --> 00:17:34,200
by making extremely
lightweight parts.

378
00:17:34,200 --> 00:17:36,633
The reason why this
is an interesting example

379
00:17:36,633 --> 00:17:38,633
is because
that same lattice structure

380
00:17:38,633 --> 00:17:40,766
now feeds into some of
the lightest weight structures

381
00:17:40,766 --> 00:17:42,233
that we know exist today.

382
00:17:42,233 --> 00:17:44,066
This was a structure
that was manufactured

383
00:17:44,066 --> 00:17:46,566
using a similar
3-D printing method

384
00:17:46,566 --> 00:17:48,733
but then electroplated
in metal,

385
00:17:48,733 --> 00:17:51,200
and it's shown sitting on top
of a dandelion.

386
00:17:51,200 --> 00:17:53,900
Extremely lightweight
but was manufactured

387
00:17:53,900 --> 00:17:56,566
using a very similar method.

388
00:17:56,566 --> 00:18:00,333
So the point of me showing this
is really that this is--

389
00:18:00,333 --> 00:18:03,166
this captures a story
of innovation and why innovation

390
00:18:03,166 --> 00:18:05,233
is so important,
because as materials change,

391
00:18:05,233 --> 00:18:09,333
as technologies change,
those allow us to then innovate

392
00:18:09,333 --> 00:18:11,166
in ways that weren't possible
5 years ago

393
00:18:11,166 --> 00:18:13,533
or 10 years ago
or 20 years ago.

394
00:18:15,600 --> 00:18:18,300
So in order to kind of
further extend the concept

395
00:18:18,300 --> 00:18:19,866
that we presented
with the FrankenEye,

396
00:18:19,866 --> 00:18:23,166
we invited several students
and personnel

397
00:18:23,166 --> 00:18:25,566
from many different
backgrounds--

398
00:18:25,566 --> 00:18:26,733
male, female,

399
00:18:26,733 --> 00:18:29,100
white, black,
and young and old,

400
00:18:29,100 --> 00:18:30,800
Republican and Democrat...

401
00:18:32,866 --> 00:18:34,733
I guess I got
carried away there.

402
00:18:34,733 --> 00:18:38,233
But we invited several students,
young engineers,

403
00:18:38,233 --> 00:18:41,733
to experiment
with the advantages

404
00:18:41,733 --> 00:18:44,366
that we could potentially see
using these methods.

405
00:18:44,366 --> 00:18:47,366
And so we formed teams of three
which were given the task

406
00:18:47,366 --> 00:18:51,700

of designing their own airplane
to image in highest definition

407
00:18:51,700 --> 00:18:53,700
an object that we were
going to place on the ground

408
00:18:53,700 --> 00:18:55,533
using their airplane.

409
00:18:55,533 --> 00:18:57,866
And the interesting thing
about the result

410
00:18:57,866 --> 00:19:00,266
of those experiments
was that they came up

411
00:19:00,266 --> 00:19:02,066
with three different
airplane designs

412
00:19:02,066 --> 00:19:04,366
that were really designed
to do the same mission.

413
00:19:05,900 --> 00:19:08,900
So this goes to say that,
many times, we limit

414
00:19:08,900 --> 00:19:12,000
the design space to the point
where we don't even consider

415
00:19:12,000 --> 00:19:14,166
ideas outside the box
that may accomplish

416
00:19:14,166 --> 00:19:16,466
the same exact mission

but in a different way.

417
00:19:16,466 --> 00:19:18,333
The first concept,
which is shown here

418
00:19:18,333 --> 00:19:22,133
by Team Hyperion, was designed
to turn into a hover,

419
00:19:22,133 --> 00:19:25,633
and once it reached a position
where it was in the vicinity

420
00:19:25,633 --> 00:19:28,300
of the image that was being--
the object being imaged,

421
00:19:28,300 --> 00:19:30,466
it would,
from that hover position,

422
00:19:30,466 --> 00:19:34,333
create a 360-degree map,

423
00:19:34,333 --> 00:19:36,300
increasing the likelihood
of it catching

424
00:19:36,300 --> 00:19:41,133
a high-definition image
of the object.

425
00:19:41,133 --> 00:19:43,666
And Team Chimaera
and Team Alconto,

426
00:19:43,666 --> 00:19:47,333
they also looked at ways
of extending

427
00:19:47,333 --> 00:19:49,133
the performance
of the fixed-wing aircraft

428
00:19:49,133 --> 00:19:53,533
by adding winglets
and enhancing the flap system.

429
00:19:53,533 --> 00:19:58,733
But this all shows that,
from a exponential--

430
00:19:58,733 --> 00:20:00,700
from a library of parts
which we created

431
00:20:00,700 --> 00:20:03,366
for the students,
there is an exponential

432
00:20:03,366 --> 00:20:05,166
design space
that can be explored.

433
00:20:05,166 --> 00:20:09,033
And maybe some designs
like the 1910 Jacobs Design

434
00:20:09,033 --> 00:20:11,866
are possible.

435
00:20:11,866 --> 00:20:14,133
The next step
of our summer task

436
00:20:14,133 --> 00:20:16,333
was to have the students
simulate how their airplane

437
00:20:16,333 --> 00:20:18,333
would perform
in an actual mission,

438
00:20:18,333 --> 00:20:19,866
and so they simulated cruise,

439
00:20:19,866 --> 00:20:22,433
they simulated hover,
they simulated

440
00:20:22,433 --> 00:20:25,000
maneuver conditions
that would place unusual,

441
00:20:25,000 --> 00:20:27,333
asymmetric loads on the wing.

442
00:20:27,333 --> 00:20:29,933
They also simulated
gimbal camera systems

443
00:20:29,933 --> 00:20:32,966
for capturing images
from the stationary platform

444
00:20:32,966 --> 00:20:36,800
of the aircraft,
and they also simulated

445
00:20:36,800 --> 00:20:39,166
high-performance,
high-lift systems,

446
00:20:39,166 --> 00:20:42,000
like the cambered flaps
system

447
00:20:42,000 --> 00:20:43,433

which is shown here.

448
00:20:43,433 --> 00:20:44,866
And so,
through those simulations,

449
00:20:44,866 --> 00:20:46,533
they gained a better
understanding of how

450
00:20:46,533 --> 00:20:48,533
these parts
would ideally perform

451
00:20:48,533 --> 00:20:51,766
in the real world
after being manufactured.

452
00:20:51,766 --> 00:20:53,833
So with the results
of those simulations,

453
00:20:53,833 --> 00:20:56,833
they then went to
hardware-in-the-loop testing.

454
00:20:56,833 --> 00:20:59,233
This is an example
of testing that was done

455
00:20:59,233 --> 00:21:01,900
on a flap system
that you saw,

456
00:21:01,900 --> 00:21:06,866
and we had some of the students
hook their autopilot

457
00:21:06,866 --> 00:21:10,866
to the hardware

and actually, you know,

458
00:21:10,866 --> 00:21:12,833
for the first time,
really see that their design

459
00:21:12,833 --> 00:21:15,133
was actually working.

460
00:21:15,133 --> 00:21:17,166
And so they're doing
some flap tests here,

461
00:21:17,166 --> 00:21:19,433
and they also do some
power-on tests--

462
00:21:19,433 --> 00:21:22,333
you can see the motor spinning--
to make sure that everything

463
00:21:22,333 --> 00:21:24,666
checks out
in terms of the power--

464
00:21:24,666 --> 00:21:26,466
power system
on the aircraft.

465
00:21:27,900 --> 00:21:29,466
So from that stage,
we understood

466
00:21:29,466 --> 00:21:31,633
that the basic design worked,
but we then needed

467
00:21:31,633 --> 00:21:34,300
to optimize them
for structural weight

468
00:21:34,300 --> 00:21:35,966
and for
other performance metrics.

469
00:21:35,966 --> 00:21:37,533
And so this is really
where the skill set

470
00:21:37,533 --> 00:21:39,300
of the students came in,
where they were able

471
00:21:39,300 --> 00:21:43,100
to apply their background
in aerodynamic structures

472
00:21:43,100 --> 00:21:46,800
and other areas
to optimize the design.

473
00:21:46,800 --> 00:21:49,033
And really what we want
is designs that look more

474
00:21:49,033 --> 00:21:50,400
like what we see in nature.

475
00:21:50,400 --> 00:21:54,300
A bird's wing
looks very interesting

476
00:21:54,300 --> 00:21:56,600
in that there's only material
where it needs to be

477
00:21:56,600 --> 00:21:58,100
in order to maintain
the certain load

478
00:21:58,100 --> 00:22:00,900
that the bird
is carrying in flight.

479
00:22:00,900 --> 00:22:03,166
And we can also think about
how this can be applied

480
00:22:03,166 --> 00:22:05,266
on the scale
of the aircraft itself

481
00:22:05,266 --> 00:22:10,900
using flexible materials,
using shape-changing materials

482
00:22:10,900 --> 00:22:12,933
that would simulate--
that would move us closer

483
00:22:12,933 --> 00:22:15,033
towards the direction
of what we see in bird flight.

484
00:22:16,700 --> 00:22:18,600
Another area
that we wanted to explore

485
00:22:18,600 --> 00:22:21,333
was how to take a cheap part
that is printed in plastic

486
00:22:21,333 --> 00:22:25,100
or in some inexpensive material
and to enhance the strength

487
00:22:25,100 --> 00:22:27,366
of that part, and we looked
at two different methods.

488
00:22:27,366 --> 00:22:29,866
One is plating on plastic--

489
00:22:29,866 --> 00:22:31,266
curing on plastic.

490
00:22:31,266 --> 00:22:34,033
Plating on plastic
is also known as electroplating,

491
00:22:34,033 --> 00:22:36,100
and it's widely used
in the jewelry industry,

492
00:22:36,100 --> 00:22:38,433
in the plumbing industry
and many other industries

493
00:22:38,433 --> 00:22:42,133
but is now being investigated
for use in the aerospace

494
00:22:42,133 --> 00:22:44,500
engineering industry.

495
00:22:44,500 --> 00:22:47,366
And we also were looking
at ways of taking carbon fiber,

496
00:22:47,366 --> 00:22:50,233
fiberglass, Kevlar,
and using them

497
00:22:50,233 --> 00:22:53,166
to mold
against a 3-D-printed part.

498
00:22:53,166 --> 00:22:56,300
The results of that

were that we showed--

499
00:22:56,300 --> 00:22:58,700
using these different prototypes
that are shown,

500
00:22:58,700 --> 00:23:02,500
that we could
enhance the strength

501
00:23:02,500 --> 00:23:04,133
of the part by
at least three times,

502
00:23:04,133 --> 00:23:07,666
making those parts
almost comparable

503
00:23:07,666 --> 00:23:09,533
to the strength
of aluminum,

504
00:23:09,533 --> 00:23:11,366
which is really impressive
for something

505
00:23:11,366 --> 00:23:13,533
that costs roughly
half the cost

506
00:23:13,533 --> 00:23:15,366
of an extruded piece
of aluminum

507
00:23:15,366 --> 00:23:18,000
of the same dimension and shape.

508
00:23:19,766 --> 00:23:21,266
Another consideration
that we would need

509
00:23:21,266 --> 00:23:23,266
to make in order
to satisfy a mission requirement

510
00:23:23,266 --> 00:23:25,566
is understanding how the sensors
play into that mission

511
00:23:25,566 --> 00:23:28,233
and how perhaps
they can be optimized

512
00:23:28,233 --> 00:23:30,566
to collect the information
that is important

513
00:23:30,566 --> 00:23:32,766
for the mission succeeding.

514
00:23:32,766 --> 00:23:34,566
And by having
a variety of sensors,

515
00:23:34,566 --> 00:23:38,333
which are then themselves
design modular to the aircraft,

516
00:23:38,333 --> 00:23:42,000
we can interchange sensors
to meet a certain requirement.

517
00:23:43,966 --> 00:23:45,533
So we talked
about modular design,

518
00:23:45,533 --> 00:23:47,666
additive manufacturing,
and now we can talk more

519
00:23:47,666 --> 00:23:50,333
about the specific missions
and the flight operations

520
00:23:50,333 --> 00:23:52,833
that are required
for getting the airplane

521
00:23:52,833 --> 00:23:56,000
into the actual mission.

522
00:23:56,000 --> 00:24:00,200
So the airworthiness process
requires that we take parts

523
00:24:00,200 --> 00:24:02,333
and we test them
to their structural

524
00:24:02,333 --> 00:24:04,866
failure point
to better understand

525
00:24:04,866 --> 00:24:06,366
the limitations
of the materials.

526
00:24:06,366 --> 00:24:09,100
And we want to make sure
that the strength of the part

527
00:24:09,100 --> 00:24:13,066
begins to reflect
the harsh environment

528
00:24:13,066 --> 00:24:15,133
that we expect to see
in certain flight conditions,

529

00:24:15,133 --> 00:24:18,766
and so, as a part of that
airworthiness review process,

530
00:24:18,766 --> 00:24:21,533
we did static testing,
which is where you take a wing

531
00:24:21,533 --> 00:24:25,700
and you load it
to the point where it strains

532
00:24:25,700 --> 00:24:28,366
and then you look
for the place where it fails

533
00:24:28,366 --> 00:24:32,533
and you try to understand
something about why it failed

534
00:24:32,533 --> 00:24:34,366
and look at ways
of reducing the weight

535
00:24:34,366 --> 00:24:36,100
so that you can still
meet the requirements

536
00:24:36,100 --> 00:24:37,633
for flight,
and this was an example

537
00:24:37,633 --> 00:24:39,233
of a static test.

538
00:24:39,233 --> 00:24:42,366
Beyond that,
when you start thinking

539
00:24:42,366 --> 00:24:45,066

about putting aircraft
into production

540
00:24:45,066 --> 00:24:47,500
or even looking
at larger-size airplanes,

541
00:24:47,500 --> 00:24:50,100
you also need confidence
in the models

542
00:24:50,100 --> 00:24:51,900
that are used to simulate
what is happening

543
00:24:51,900 --> 00:24:54,700
in the actual physical test.

544
00:24:54,700 --> 00:24:57,633
So finite element modeling
is very important

545
00:24:57,633 --> 00:24:59,133
to improving that understanding,

546
00:24:59,133 --> 00:25:00,666
particularly
if you're interested

547
00:25:00,666 --> 00:25:02,466
in putting something
into production;

548
00:25:02,466 --> 00:25:06,766
you don't want to have to do
a large number of static tests,

549
00:25:06,766 --> 00:25:08,833
but you would rather
have confidence in your model

550
00:25:08,833 --> 00:25:12,333
matching the static test
of the sacrificial part.

551
00:25:14,166 --> 00:25:16,466
One of the other questions
that we wanted to answer,

552
00:25:16,466 --> 00:25:19,700
now that we had explored methods
of how to improve the strength

553
00:25:19,700 --> 00:25:22,533
of 3-D-printed parts was,
"How big of an airplane

554
00:25:22,533 --> 00:25:24,566
"can we build
using the limitations

555
00:25:24,566 --> 00:25:26,066
of the existing materials?"

556
00:25:26,066 --> 00:25:27,200
And this was a study

557
00:25:27,200 --> 00:25:29,200
looking at the different
possible options

558
00:25:29,200 --> 00:25:34,333
for increasing the size
of the aircraft,

559
00:25:34,333 --> 00:25:36,500
limited by
the root bending moment,

560

00:25:36,500 --> 00:25:40,000
which is the integration
of the lift along the wing.

561
00:25:40,000 --> 00:25:42,500
And so the answer
to the question

562
00:25:42,500 --> 00:25:44,333
is really
that it really depends

563
00:25:44,333 --> 00:25:46,166
on what the airplane
is designed to do.

564
00:25:46,166 --> 00:25:49,000
Most large airplanes that
are long-endurance airplanes

565
00:25:49,000 --> 00:25:52,100
are designed to be
somewhat of high-altitude,

566
00:25:52,100 --> 00:25:53,266
long-endurance aircraft--

567
00:25:53,266 --> 00:25:56,400
the HALE UAV
that you've seen

568
00:25:56,400 --> 00:25:58,066
certain entities pursuing.

569
00:25:58,066 --> 00:25:59,233
But they're really designed

570
00:25:59,233 --> 00:26:00,766
against
the structural limitations

571
00:26:00,766 --> 00:26:02,633
of the material being used
in the wing.

572
00:26:02,633 --> 00:26:05,266
Another alternative
is that you can design

573
00:26:05,266 --> 00:26:06,600
much lighter-weight
structures

574
00:26:06,600 --> 00:26:08,233
that have some docking feature

575
00:26:08,233 --> 00:26:10,733
where there's
minimal load transfer

576
00:26:10,733 --> 00:26:12,866
between individual components,

577
00:26:12,866 --> 00:26:14,800
but they can still
share information.

578
00:26:14,800 --> 00:26:17,666
A good example is of sharing

579
00:26:17,666 --> 00:26:20,366
of actual
physical material

580
00:26:20,366 --> 00:26:22,633
is air-to-air refueling.

581
00:26:22,633 --> 00:26:27,900
If an airplane is refueling

from a tanker, for instance,

582
00:26:27,900 --> 00:26:31,200
there's minimal load transfer,
but still, the physical fuel

583
00:26:31,200 --> 00:26:33,133
is being transferred,
and so I think this

584
00:26:33,133 --> 00:26:34,966
is really--
has a great potential

585
00:26:34,966 --> 00:26:37,700
to produce aircraft
that are just as efficient

586
00:26:37,700 --> 00:26:41,333
as some of the HALE UAVs
but are extremely lightweight

587
00:26:41,333 --> 00:26:46,100
in their design,
and this is an unexplored area.

588
00:26:46,100 --> 00:26:47,866
Another question
that we had to answer

589
00:26:47,866 --> 00:26:49,333
related to the strength
of the part

590
00:26:49,333 --> 00:26:52,200
is how would that part
survive in a crash landing,

591
00:26:52,200 --> 00:26:54,966
and so we did

catapult launch tests,

592
00:26:54,966 --> 00:26:57,000
which are shown here,
where the aircraft

593
00:26:57,000 --> 00:26:59,533
is launched with 20 pounds
of weight loaded

594
00:26:59,533 --> 00:27:01,400
into the center fuselage
to simulate

595
00:27:01,400 --> 00:27:04,300
a much larger airplane,
and as you see in the test,

596
00:27:04,300 --> 00:27:07,633
the airplane just breaks apart,
which is great.

597
00:27:07,633 --> 00:27:09,866
It confused
some of the students at first

598
00:27:09,866 --> 00:27:12,633
because they didn't know
whether it was--

599
00:27:12,633 --> 00:27:14,600
it should be thought of
as a failure or a success,

600
00:27:14,600 --> 00:27:16,466
but for us,
it was a success,

601
00:27:16,466 --> 00:27:18,700
because we learned more

about our launcher system,

602
00:27:18,700 --> 00:27:20,533
and we gained confidence
in the ability

603
00:27:20,533 --> 00:27:23,400
for that launcher system
to handle larger airplanes.

604
00:27:23,400 --> 00:27:25,633
And so this is an example
of some of the information

605
00:27:25,633 --> 00:27:27,866
that we got from our
catapult launch testing,

606
00:27:27,866 --> 00:27:30,933
where the accelerations
for the launcher

607
00:27:30,933 --> 00:27:35,700
matched those that we needed
to launch much larger airplanes,

608
00:27:35,700 --> 00:27:40,200
and we went through many
different iterations of that.

609
00:27:40,200 --> 00:27:42,533
So now going to flight,
we take our simulations,

610
00:27:42,533 --> 00:27:45,600
and then we try
to learn something

611
00:27:45,600 --> 00:27:48,933
from the flight testing

to calibrate our simulations

612
00:27:48,933 --> 00:27:52,333
to the actual data
that we collect in flight.

613
00:27:52,333 --> 00:27:54,500
And so this is one of
the first flight tests.

614
00:27:54,500 --> 00:27:56,633
As you saw previously,
it was a little rough

615
00:27:56,633 --> 00:27:59,966
coming off of--
of the catapult launcher,

616
00:27:59,966 --> 00:28:02,200
but luckily by that time,
we had de-risked

617
00:28:02,200 --> 00:28:05,900
the launcher design itself
so that the real worry

618
00:28:05,900 --> 00:28:07,733
was how the airplane
would perform in flight.

619
00:28:07,733 --> 00:28:09,433
And this was some video
that was taken.

620
00:28:09,433 --> 00:28:11,500
We're located
in the right corner

621
00:28:11,500 --> 00:28:15,533
over there on the ground

as the airplane's flying by.

622
00:28:15,533 --> 00:28:17,866
And then the question was,
"Now that we have

623
00:28:17,866 --> 00:28:20,733
"a better understanding
of how the airplane performs,

624
00:28:20,733 --> 00:28:25,033
can we understand and map
the aerodynamic improvement

625
00:28:25,033 --> 00:28:28,100
to the models
that we've been generating?"

626
00:28:28,100 --> 00:28:30,466
And by doing that,
we can now start to build

627
00:28:30,466 --> 00:28:33,600
a way of the computer
or the laptop

628
00:28:33,600 --> 00:28:35,366
that's being used
as a ground station

629
00:28:35,366 --> 00:28:41,000
to directly control the aircraft
instead of having an RC pilot

630
00:28:41,000 --> 00:28:42,433
fly the aircraft.

631
00:28:42,433 --> 00:28:44,066
So this is known
as autonomous flight,

632
00:28:44,066 --> 00:28:45,633
where we want the airplane
to be flown

633
00:28:45,633 --> 00:28:49,033
by the computer
instead of by a pilot.

634
00:28:49,033 --> 00:28:51,466
And so we can
do certain experiments

635
00:28:51,466 --> 00:28:54,400
with waypoint navigation,
where we set up the flight path

636
00:28:54,400 --> 00:28:57,433
in the software that
the airplane is going to take,

637
00:28:57,433 --> 00:29:00,566
and these are actually the--
the actual coordinates

638
00:29:00,566 --> 00:29:01,900
of the airplane
as it's following

639
00:29:01,900 --> 00:29:05,733
that flight path,
which has been set up.

640
00:29:05,733 --> 00:29:09,000
So this is an example
of how we took that design,

641
00:29:09,000 --> 00:29:12,266
which we now had
a better understanding of how--

642
00:29:12,266 --> 00:29:14,466
how it flew
and how efficient it was

643
00:29:14,466 --> 00:29:17,066
to an autonomous flight test.

644
00:29:18,766 --> 00:29:20,466
One of the final considerations

645
00:29:20,466 --> 00:29:21,566
I want to mention here

646
00:29:21,566 --> 00:29:24,066
is that the useful life

647
00:29:24,066 --> 00:29:25,800
of an airplane depends also

648
00:29:25,800 --> 00:29:27,266
on how it's being used, and we

649
00:29:27,266 --> 00:29:29,066
often refer to this as being

650
00:29:29,066 --> 00:29:30,366
the dynamic loading environment

651
00:29:30,366 --> 00:29:31,833
of an aircraft.

652
00:29:31,833 --> 00:29:33,000
We tend to think

653
00:29:33,000 --> 00:29:35,400
that the more material we add

654
00:29:35,400 --> 00:29:36,566
to an airplane, the longer

655
00:29:36,566 --> 00:29:38,166
a life it will have, but this

656
00:29:38,166 --> 00:29:39,633
is kind of counterintuitive

657
00:29:39,633 --> 00:29:42,166
to what actually--what we see.

658
00:29:42,166 --> 00:29:43,833
Airplanes
that are usually designed

659
00:29:43,833 --> 00:29:45,900
to a higher safety factor--
meaning more weight

660
00:29:45,900 --> 00:29:49,133
is put in the wing--
degrade very quickly

661
00:29:49,133 --> 00:29:52,266
because they operate
in very extreme environments

662
00:29:52,266 --> 00:29:56,100
that put certain stresses
on the materials.

663
00:29:56,100 --> 00:29:57,633
We can also compare
what we see

664
00:29:57,633 --> 00:30:00,000
in the aircraft design world
to what we see

665
00:30:00,000 --> 00:30:02,700
in the natural world
with bird flight,

666
00:30:02,700 --> 00:30:06,566
and, surprisingly,
some of the most long-endurance

667
00:30:06,566 --> 00:30:09,233
performance birds,
like the albatross,

668
00:30:09,233 --> 00:30:10,733
are ones that live the longest.

669
00:30:10,733 --> 00:30:12,633
So maybe that gives us
some lessons

670
00:30:12,633 --> 00:30:15,400
about how we should also
be more conscious of our health

671
00:30:15,400 --> 00:30:17,733
and, you know, what type of
stresses we have on our bodies

672
00:30:17,733 --> 00:30:20,300
to live as long as we can.

673
00:30:20,300 --> 00:30:24,133
Finally, I'm going to end up
with a summary and conclusions.

674
00:30:24,133 --> 00:30:26,533
So, the key elements
that made this project a success

675

00:30:26,533 --> 00:30:27,533
were that we were able to

676
00:30:27,533 --> 00:30:29,466
leverage open-source avionics;

677
00:30:29,466 --> 00:30:30,566
we were able to leverage

678
00:30:30,566 --> 00:30:31,866
modular design reuse

679
00:30:31,866 --> 00:30:33,700
of the DragonEye components

680
00:30:33,700 --> 00:30:36,000
and rapid prototyping provided

681
00:30:36,000 --> 00:30:37,600
to us through the facilities

682
00:30:37,600 --> 00:30:39,733
available in the NASA SpaceShop.

683
00:30:39,733 --> 00:30:41,933
And we were also able
to leverage the use

684
00:30:41,933 --> 00:30:45,100
of the Airworthiness Flight
Review Board

685
00:30:45,100 --> 00:30:47,733
that is located here
at NASA Ames,

686
00:30:47,733 --> 00:30:50,666
which walked with us
every step of the way

687
00:30:50,666 --> 00:30:53,533
through our
flight testing process.

688
00:30:53,533 --> 00:30:57,033
And by taking advantage
of these three core elements,

689
00:30:57,033 --> 00:31:00,833
we were able to achieve flight
in less than eight weeks.

690
00:31:00,833 --> 00:31:03,700
This is less than two months
going from a paper design

691
00:31:03,700 --> 00:31:07,966
all the way to the final flying
autonomous flight.

692
00:31:07,966 --> 00:31:11,733
And not only did we do it
one time; we did it twice.

693
00:31:11,733 --> 00:31:13,800
So this is an example of some

694
00:31:13,800 --> 00:31:15,733
of the 3-D printed parts
that we came up with,

695
00:31:15,733 --> 00:31:18,133
some of them using
the lattice type designs.

696
00:31:18,133 --> 00:31:21,500
This design was done by Dave--

697

00:31:21,500 --> 00:31:25,633
by Kenny Chong,
who is a researcher here.

698
00:31:25,633 --> 00:31:28,500
And we also were able to take
an existing wing

699
00:31:28,500 --> 00:31:30,900
that was made out of pink foam
and re-create it

700
00:31:30,900 --> 00:31:33,400
using 3-D printed parts.

701
00:31:33,400 --> 00:31:36,533
This is, essentially, the idea
of 3-D printing a fuel tank,

702
00:31:36,533 --> 00:31:39,700
where the airplane can be--

703
00:31:39,700 --> 00:31:41,700
the parts can be designed
so that they fit together

704
00:31:41,700 --> 00:31:43,700
in a way that
you just simply add fuel

705
00:31:43,700 --> 00:31:46,133
in the middle of the wing,

706
00:31:46,133 --> 00:31:49,900
and you can snap it
on your airplane and go and fly.

707
00:31:49,900 --> 00:31:52,400
And so this was
a major contribution, I think,

708
00:31:52,400 --> 00:31:57,000
in the area of the wing design
using 3-D printing.

709
00:31:57,000 --> 00:31:59,466
And as I mentioned before,
concept of flight,

710
00:31:59,466 --> 00:32:02,433
autonomous flight,
in less than eight weeks

711
00:32:02,433 --> 00:32:05,900
by leveraging the elements
that I showed earlier.

712
00:32:05,900 --> 00:32:11,566
And so we want to--
so this was

713
00:32:11,566 --> 00:32:14,166
an extremely successful project
from my perspective.

714
00:32:14,166 --> 00:32:18,200
The team members that
contributed and the mentors

715
00:32:18,200 --> 00:32:19,666
deserve all the credit
for this,

716
00:32:19,666 --> 00:32:22,366
and I'm just
their spokesperson.

717
00:32:22,366 --> 00:32:26,566
But some of that success
was reflected

718
00:32:26,566 --> 00:32:28,666
in the media coverage
that we received.

719
00:32:28,666 --> 00:32:31,400
We had a very interesting
Halloween article

720
00:32:31,400 --> 00:32:36,133
that was published with--
referring to how we were able

721
00:32:36,133 --> 00:32:38,400
to take these airplanes
and put them together

722
00:32:38,400 --> 00:32:40,600
almost like
a Frankenstein monster.

723
00:32:40,600 --> 00:32:43,833
And one of the other
interesting insights

724
00:32:43,833 --> 00:32:46,133
that I derived
from this project

725
00:32:46,133 --> 00:32:49,600
was that in the course
of eight weeks,

726
00:32:49,600 --> 00:32:53,500
these student teams
all came up with solutions

727
00:32:53,500 --> 00:32:55,400
very different
to the same problem.

728
00:32:55,400 --> 00:32:57,933
And if you take all of those--
the three solutions

729
00:32:57,933 --> 00:33:00,833
and you superimpose them,
you get something that

730
00:33:00,833 --> 00:33:02,633
you may have seen
on the way in,

731
00:33:02,633 --> 00:33:04,200
the Super FrankenEye,

732
00:33:04,200 --> 00:33:06,100
superimposed FrankenEye.

733
00:33:06,100 --> 00:33:08,233
So the ironic thing
about this design

734
00:33:08,233 --> 00:33:12,466
is that it looks very similar
to a Russian design, actually,

735
00:33:12,466 --> 00:33:16,166
that currently holds
15 world records.

736
00:33:16,166 --> 00:33:18,200
Very different scale,

737
00:33:18,200 --> 00:33:19,600
very different application,

738
00:33:19,600 --> 00:33:23,166
but the point

is that by using

739
00:33:23,166 --> 00:33:26,566
the rapid manufacturing
and rapid prototyping approach

740
00:33:26,566 --> 00:33:29,400
we were able to kind of start
focusing down

741
00:33:29,400 --> 00:33:31,233
on the elements that were
most important

742
00:33:31,233 --> 00:33:32,700
for improving performance,

743
00:33:32,700 --> 00:33:35,266
and now we were able
to generate a design

744
00:33:35,266 --> 00:33:38,966
that we would expect
to be an optimal performer

745
00:33:38,966 --> 00:33:42,166
if it, say, were scaled up
to a larger size.

746
00:33:42,166 --> 00:33:46,166
And we also were able to--
I was able to meet

747
00:33:46,166 --> 00:33:48,366
President Obama
on one of his visits,

748
00:33:48,366 --> 00:33:51,733
and I'm very grateful for
the support that was provided

749
00:33:51,733 --> 00:33:54,800
with his visit.

750
00:33:54,800 --> 00:33:57,933
And the final comment
was that we--

751
00:33:57,933 --> 00:34:00,833
in one of our articles,
we were actually given

752
00:34:00,833 --> 00:34:03,233
a new word,
"Frankensteined,"

753
00:34:03,233 --> 00:34:06,166
which I'm really happy about.

754
00:34:06,166 --> 00:34:08,166
And I think people
just get the idea that

755
00:34:08,166 --> 00:34:10,766
we're trying to reuse,
we're trying to repurpose,

756
00:34:10,766 --> 00:34:13,200
we're trying to recycle
existing components

757
00:34:13,200 --> 00:34:15,200
but just re-architect them
in a different way

758
00:34:15,200 --> 00:34:18,200
that improves
their performance.

759

00:34:18,200 --> 00:34:20,966
And we've also seen
that the aviation industry

760
00:34:20,966 --> 00:34:23,033
has taken some interest
in this.

761
00:34:23,033 --> 00:34:25,466
These are some examples--
recent examples

762
00:34:25,466 --> 00:34:27,733
of how 3-D printing
and modular design

763
00:34:27,733 --> 00:34:29,433
are being used
in different ways.

764
00:34:29,433 --> 00:34:31,766
And we only expect
the future to be

765
00:34:31,766 --> 00:34:33,666
much brighter
in these areas.

766
00:34:33,666 --> 00:34:36,400
And the potential cost savings
is going to be reflected

767
00:34:36,400 --> 00:34:39,733
as we see some of these methods
potentially applied

768
00:34:39,733 --> 00:34:42,666
to larger aircraft systems.

769
00:34:42,666 --> 00:34:45,833

I would say that this area
is an emerging area

770
00:34:45,833 --> 00:34:47,400
that needs more research.

771
00:34:47,400 --> 00:34:50,766
It needs more attention,
but it has the potential

772
00:34:50,766 --> 00:34:55,066
to really impact the industry
in a big way.

773
00:34:55,066 --> 00:34:58,500
So with that, I will...

774
00:35:01,800 --> 00:35:04,933
With that, I will ask
for your questions.

775
00:35:04,933 --> 00:35:07,800
The next slide is just--yeah.

776
00:35:07,800 --> 00:35:10,366
With that, I will ask
for your questions.

777
00:35:10,366 --> 00:35:13,366
[applause]

778
00:35:17,500 --> 00:35:19,500
- Thank you, Kevin.
- Yeah, thank you.

779
00:35:19,500 --> 00:35:22,333
- So if you have questions,
please line up

780

00:35:22,333 --> 00:35:24,266
on the microphone
in the center aisle

781
00:35:24,266 --> 00:35:26,866
and ask one question only.

782
00:35:29,333 --> 00:35:31,833
Okay.

783
00:35:31,833 --> 00:35:34,533
- Hi, and thank you for
the lecture. Very interesting.

784
00:35:34,533 --> 00:35:36,200
I was wondering if there's
any crossover

785
00:35:36,200 --> 00:35:38,233
with other industries
that could clearly benefit

786
00:35:38,233 --> 00:35:41,333
from the whole
modular design idea.

787
00:35:41,333 --> 00:35:43,533
In other words, like,
buildings or automobiles

788
00:35:43,533 --> 00:35:45,700
or, you know, subways,
you know?

789
00:35:45,700 --> 00:35:50,666
Has there been any sharing
of lessons learned, et cetera?

790
00:35:50,666 --> 00:35:52,666
- Yeah,

thanks for the question.

791
00:35:52,666 --> 00:35:54,666
We see modular design
all around us.

792
00:35:54,666 --> 00:35:57,466
Almost every assembly
or complex system

793
00:35:57,466 --> 00:35:59,066
that we deal with
on a day-to-day basis

794
00:35:59,066 --> 00:36:03,833
has many components,
but typically those components

795
00:36:03,833 --> 00:36:06,433
are just added together
using screws or bolts

796
00:36:06,433 --> 00:36:08,666
or in different ways.

797
00:36:08,666 --> 00:36:11,766
I think the thing that is unique
about this specific design

798
00:36:11,766 --> 00:36:15,400
is that we approach aircraft
design from the perspective

799
00:36:15,400 --> 00:36:18,100
that parts
have to be interchangeable.

800
00:36:18,100 --> 00:36:19,533
We want simple interfaces,

801
00:36:19,533 --> 00:36:21,533
mechanical and electrical
interfaces,

802
00:36:21,533 --> 00:36:24,533
to make plugging in a new part
just as simple

803
00:36:24,533 --> 00:36:28,366
as plugging in a device
into a USB drive on a computer.

804
00:36:28,366 --> 00:36:33,300
And so I think we can
leverage lessons learned

805
00:36:33,300 --> 00:36:35,733
from other industries
like the computer industry

806
00:36:35,733 --> 00:36:38,100
and like many of the other
industries that produce

807
00:36:38,100 --> 00:36:41,466
these complex systems
that have multiple parts.

808
00:36:43,666 --> 00:36:46,266
- Hi, I had a question
about scaling

809
00:36:46,266 --> 00:36:47,900
that you touched
a little bit on.

810
00:36:47,900 --> 00:36:50,366
So there's a big difference
in material properties

811
00:36:50,366 --> 00:36:53,033
between what you can 3-D print
and what traditionally

812
00:36:53,033 --> 00:36:55,033
is used in big airplanes.

813
00:36:55,033 --> 00:36:58,366
So I imagine
that as you go smaller,

814
00:36:58,366 --> 00:37:01,966
those kinds of restrictions
get easier to deal with.

815
00:37:01,966 --> 00:37:05,333
So did you guys come up with
any kind of estimate

816
00:37:05,333 --> 00:37:08,333
on how big of an airplane
or what kind of wing loading

817
00:37:08,333 --> 00:37:11,266
or some other metric
that you can reach

818
00:37:11,266 --> 00:37:13,833
using these kinds
of approaches?

819
00:37:13,833 --> 00:37:16,500
- You bring up some
very important points.

820
00:37:16,500 --> 00:37:20,300
Large airplanes, specifically,
are in a class of their own

821

00:37:20,300 --> 00:37:24,266
because they use
parts that are

822
00:37:24,266 --> 00:37:27,066
extremely strong
and lightweight.

823
00:37:27,066 --> 00:37:29,100
For the purposes
of this project,

824
00:37:29,100 --> 00:37:30,900
we were really focused on
unmanned aircraft

825
00:37:30,900 --> 00:37:34,433
because we saw that
as the low-hanging fruit

826
00:37:34,433 --> 00:37:36,066
because we didn't--
we weren't putting

827
00:37:36,066 --> 00:37:40,133
people's lives at risk
by flying an unmanned airplane.

828
00:37:40,133 --> 00:37:42,800
I think as the materials
that we see in 3-D printing

829
00:37:42,800 --> 00:37:45,800
improve and become stronger,
which we expect they will,

830
00:37:45,800 --> 00:37:48,800
we can then start to scale up
to larger sizes.

831

00:37:48,800 --> 00:37:51,500
One of the aircraft
that we simulated

832
00:37:51,500 --> 00:37:55,733
and some of the results
that were shown

833
00:37:55,733 --> 00:37:58,833
was actually looking
at a 16U design

834
00:37:58,833 --> 00:38:01,400
based on the DragonEye concept,

835
00:38:01,400 --> 00:38:04,566
and it was approximately
a 60-foot airplane.

836
00:38:04,566 --> 00:38:07,033
So at that span,
there are also other questions

837
00:38:07,033 --> 00:38:09,100
that need to be addressed like,
"How do you control it?

838
00:38:09,100 --> 00:38:11,033
How do you launch it?"

839
00:38:11,033 --> 00:38:13,200
And we think this
is just the very beginning

840
00:38:13,200 --> 00:38:15,366
of where it's going.

841
00:38:15,366 --> 00:38:19,133
Hope that answered
your question.

842
00:38:19,133 --> 00:38:20,133
- Hi, I have a question

843
00:38:20,133 --> 00:38:21,566
about the additive manufacturing

844
00:38:21,566 --> 00:38:23,966
and the modular design combined.

845
00:38:23,966 --> 00:38:26,533
I assume there's some type
of efficiency loss

846
00:38:26,533 --> 00:38:29,033
for the structural mass
when you look

847
00:38:29,033 --> 00:38:31,600
at adding parts together
at the joints.

848
00:38:31,600 --> 00:38:34,033
Can you comment
as to what type of degree

849
00:38:34,033 --> 00:38:37,500
of efficiency loss you get
by using a modular design?

850
00:38:37,500 --> 00:38:40,966
- Right, so one of
the things that is worth noting

851
00:38:40,966 --> 00:38:46,633
is when you look at aerodynamic
efficiency of aircraft,

852
00:38:46,633 --> 00:38:48,666

it really--

853
00:38:48,666 --> 00:38:50,966
Aerodynamic efficiency
can be achieved

854
00:38:50,966 --> 00:38:55,066
in many different ways
by using biplane wings

855
00:38:55,066 --> 00:38:58,666
or using non-planar structures.

856
00:38:58,666 --> 00:39:00,900
What really matters in terms
of aerodynamic efficiency

857
00:39:00,900 --> 00:39:03,466
is what the lift distribution
looks like

858
00:39:03,466 --> 00:39:05,766
across the configuration.

859
00:39:05,766 --> 00:39:08,366
And we often account for
what that lift distribution

860
00:39:08,366 --> 00:39:10,233
looks like by looking
in the truss plane,

861
00:39:10,233 --> 00:39:14,266
which is actually several spans
behind the airplane.

862
00:39:14,266 --> 00:39:16,833
So from an aerodynamic
efficiency perspective,

863
00:39:16,833 --> 00:39:20,400
we can achieve
similar performance

864
00:39:20,400 --> 00:39:22,266
using modular designs

865
00:39:22,266 --> 00:39:27,166
that have
structurally weak parts.

866
00:39:27,166 --> 00:39:30,533
But from the structural
efficiency perspective,

867
00:39:30,533 --> 00:39:32,833
the design of the joints
can be extremely important

868
00:39:32,833 --> 00:39:35,066
for the application
that is mentioned.

869
00:39:35,066 --> 00:39:37,166
In one of the earlier charts
I showed,

870
00:39:37,166 --> 00:39:40,366
a self-docking structure
can be designed

871
00:39:40,366 --> 00:39:43,433
to have very weak joints,
but it just needs

872
00:39:43,433 --> 00:39:45,500
to hold the position required
to maintain

873

00:39:45,500 --> 00:39:47,566
the aerodynamic efficiency
benefit.

874
00:39:47,566 --> 00:39:49,333
That's just an example.

875
00:39:49,333 --> 00:39:50,766
But typically what we see

876
00:39:50,766 --> 00:39:54,266
in most high-altitude airplane
designs is that

877
00:39:54,266 --> 00:39:56,833
those designs are really pushing
the limits of the structure.

878
00:39:56,833 --> 00:39:58,900
And I think
there are opportunities

879
00:39:58,900 --> 00:40:01,366
that perhaps don't push
the limits of the structure,

880
00:40:01,366 --> 00:40:06,800
but more focused
on the control challenges.

881
00:40:06,800 --> 00:40:08,133
- Thanks for your talk, Kevin.

882
00:40:08,133 --> 00:40:10,333
Could you talk a little bit
about how you would tune

883
00:40:10,333 --> 00:40:12,700
the control laws
for these planes,

884
00:40:12,700 --> 00:40:15,366
given one design or the other?

885
00:40:15,366 --> 00:40:18,366
- Right, so for the purposes
of our project,

886
00:40:18,366 --> 00:40:22,233
which was on a short time scale,

887
00:40:22,233 --> 00:40:25,800
on a two-month development
period,

888
00:40:25,800 --> 00:40:28,933
we used open source
simulation hardware,

889
00:40:28,933 --> 00:40:31,200
"Mission Planner,"
and "X-Plane,"

890
00:40:31,200 --> 00:40:34,200
to simulate the flight
performance of the aircraft,

891
00:40:34,200 --> 00:40:38,566
and those software tools
allow us to build

892
00:40:38,566 --> 00:40:41,666
a virtual flight dynamic model
of the design.

893
00:40:41,666 --> 00:40:44,866
In a more rigorous--

894
00:40:44,866 --> 00:40:48,033

For more rigorous design,
we would actually go into

895
00:40:48,033 --> 00:40:50,900
calculating stability based--
using stability derivatives

896
00:40:50,900 --> 00:40:53,300
and those type of things,
but for the purposes

897
00:40:53,300 --> 00:40:54,666
of our experimental project,

898
00:40:54,666 --> 00:40:56,733
we relied
on the flight dynamic model

899
00:40:56,733 --> 00:41:01,300
being created
by the flight simulator.

900
00:41:06,000 --> 00:41:08,066
- Please join me
in thanking Kevin Reynolds

901
00:41:08,066 --> 00:41:10,966
for an excellent seminar.

902
00:41:10,966 --> 00:41:13,966
[applause]