UNIVERSITY OF SOUTHAMPTON

UAV Smart Wing - a Control Systems study

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Declaration

I, Bhagyesh Govilkar declare that this thesis and the work presented in it are my own and has been generated by me as the result of my own original research. I confirm that:

1. This work was done wholly or mainly while in candidature for a degree at this University;
2. Where any part of this thesis has previously been submitted for any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. None of this work has been published before submission.

Abstract

Unmanned Aerial Vehicles are becoming increasingly mainstream. With faster and more efficient ways of manufacturing such as 3D printing gaining momentum, this will only serve to bolster the emerging market. The University of Southampton's SULSA project (Southampton University Laser Sintered Aircraft) produced an UAV that was made entirely from 3D printed parts.

There are several contemporary and potential applications of UAVs: they are widely used in agriculture to give farmers a detailed picture of the health of their farm, the amount of resources such as pesticides required and they can help cut down on labour costs; they are already being used in the defence sector mostly to carry out surveillance and reconnaissance activities, a handful are being used for offensive operations such as the MQ-9 Reaper.

With this increasing usage of UAVs, there is a strong need for a control system that can give the user a stable, reliable and robust aircraft. The aim is to reduce the frequency of UAVs crashing, increase the life-span and reduce the maintenance costs.

In this project, I will be looking specifically at a phenomenon known as a "short-period oscillation". This is one of the two longitudinal dynamic modes that occur on every aircraft, the other being a "phugoid oscillation". Short-period oscillations are characterised by the rapid decay and high frequency. A typical SPO can settle within a second and can occurs at 1-2Hz. A pilot can induce a SPO by a sharp pitch input. They can also naturally occur due to a gust (impulsive increase/decrease in airspeed and/or angle of attack).

A UAV control system that does not have a SPO model is vulnerable to growing instability. It can act to reinforce the oscillation instead of canceling them. Thus it is important to systematically analyse and design a model that can handle a SPO.

Acknowledgements

I would like to acknowledge my supervisor, Dr T. Glyn Thomas who provided me with guidance every step of the way and supported my ideas that enabled me to complete this project. . .

List of Abbreviations

LAH	**L**ist **A**bbreviations **H**ere
WSF	**W**hat (it) **S**tands **F**or

Physical Constants

Speed of Light $c_0 = 2.997\,924\,58 \times 10^{8}\,\mathrm{m\,s^{-1}}$ (exact)

List of Symbols

a	distance	m
P	power	W ($J\,s^{-1}$)
ω	angular frequency	rad

Contents

Chapter 1

Background

Chapter 2

Setting up

Appendix A

Manufacturing and assembly

The main wing was split into four parts: the two ends of the wings, the middle section (as shown in figure 4.1) and the flap. Different manufacturing processes had to be utilised to obtain these parts quickly and of sufficient quality.

The middle section is geometrically complex due to the presence of the pressure tappings. It is not very practical to hand craft the part and not feasible through 2D processes such as laser cutting or foam cutting due to the 3D geometric features. 3D printing is the only process that is suitable and available for this component. Unfortunately, the span of the wing is too great (30cm) for the 3D printer so to ends of the wing need to be extended. The 3D printed part was made 20cm wide.

To extend the wing by 5cm each side, the profile of the middle section was saved as a .dxf file. This profile was laser cut out of a 5mm thick plywood 20 times and glued together side-to-side.

The flap was made similarly. The profile was laser cut 60 times and glued together.

The main wing has been supported and mounted through two 6mm carbon fibre rods that go through the wing and attach to some fixtures on the walls of the tunnel. These fixtures were designed specifically for this project. Looking upstream, the fixture disc on the right hand side (Figure 4.3) has holes for the carbon fibre rods, a cut out for the flap servo to be mounted in, six holes for the PVC tubes connecting the pressure tappings to the sensors and several holes near the edges to allow changing the angle of attack of the wing to a desired setting. The angular separation between these holes is 5°. The pressure tappings end at the right side of the middle section of the wing. Sections of a 4mm (outer diameter) copper pipe were placed in these holes and glued in place. These created "ports" which allowed easy and secure connection of the pressure tappings to the pressure sensors. Six equal sections of 3mm PVC tube(inner diameter) were cut to facilitate this connection. One end of each tube was secured to the pressure sensor ports, the other end had to be heated and expanded to fit onto the larger copper ports on the wing. This provided an excellent tight seal which is beneficial because less pressure will be lost.

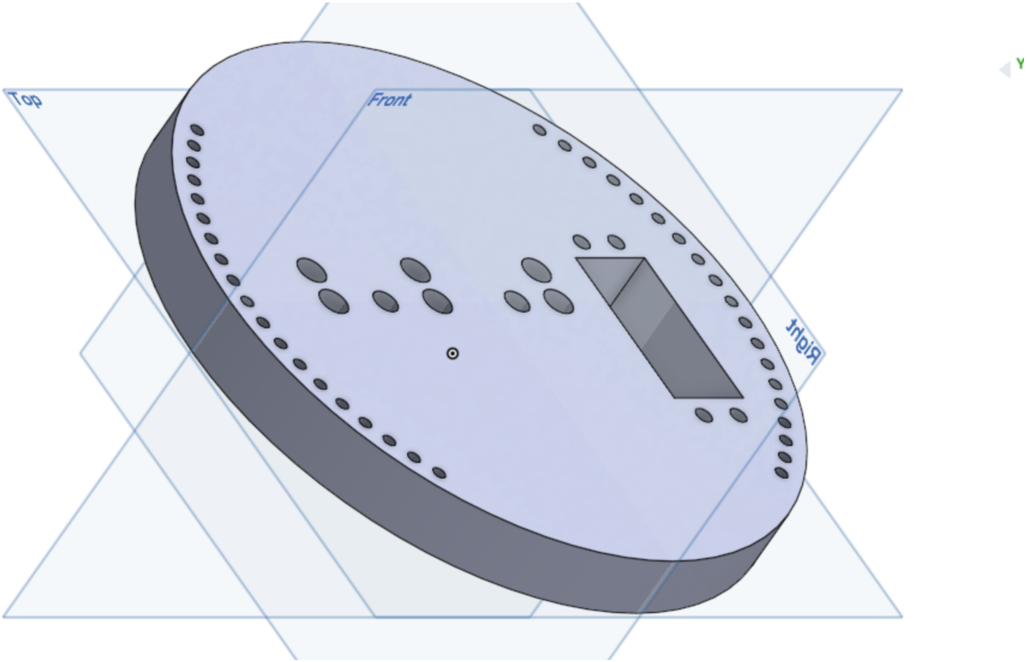

FIGURE A.1: Fixture on the right hand side of the wind tunnel

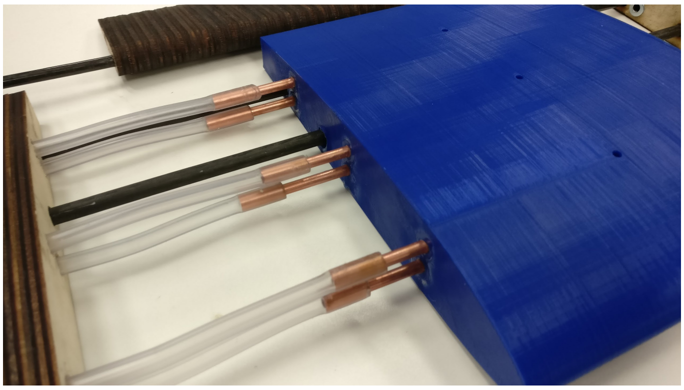

FIGURE A.2: Picture of the PVC tubing and the midsection of the wing

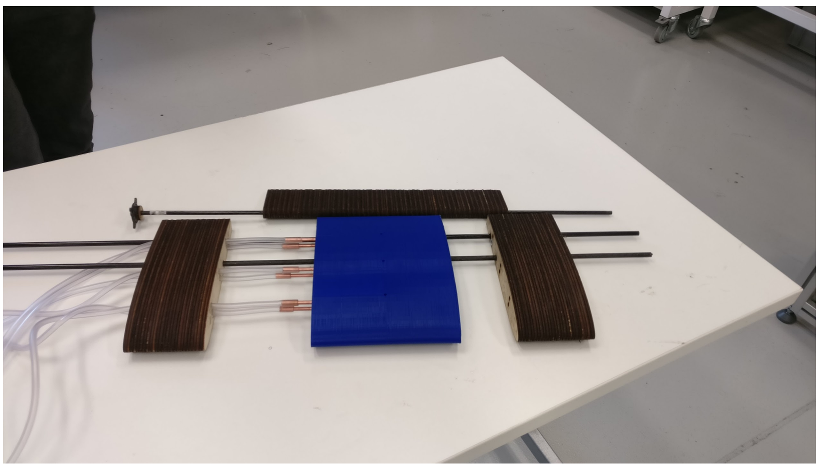

FIGURE A.3: Picture showing how the different parts of the wing were integrated

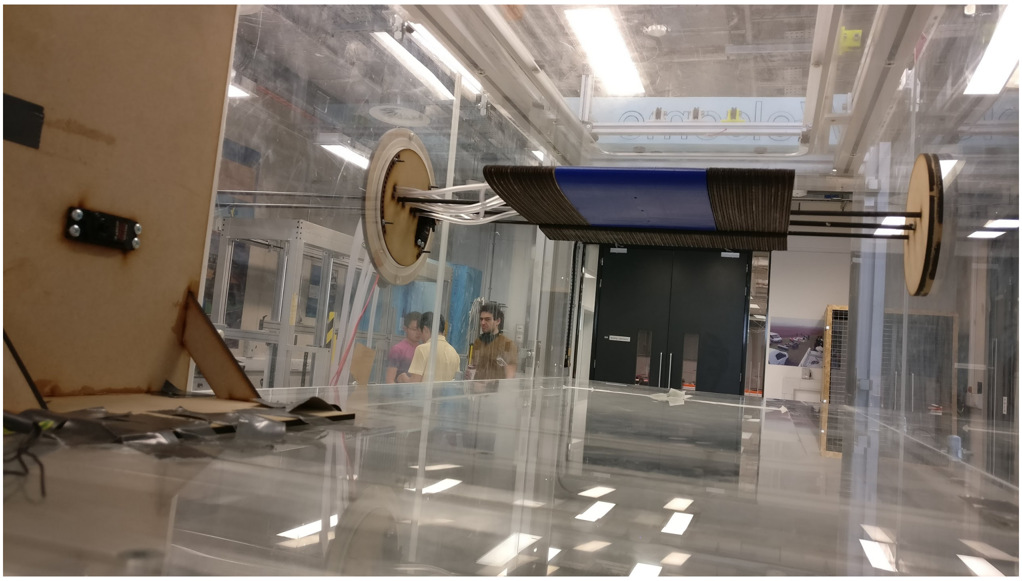

FIGURE A.4: Picture showing the main wing assembly in the wind tunnel

Appendix B

Risk Assessment

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RECORD OF RISK ASSESSMENT

Title of the risk assessment	Smart wing project
Date risk assessment carried out	16/04/2018
Describe the work being assessed	Control system designed to suppress short period oscillations
Describe the location at which the work is being carried out	Building 13, Highfield Campus / Design studio, Boldrewood Campus
Where appropriate list the individuals doing the work and the dates/times when the work will be carried out	Bhagyesh Govilkar, Semester 2 2018
List any other generic or specific risk assessments or other documents that relate to this assessment-use hyperlinks if possible	
Name and post of risk assessor	Bhagyesh Govilkar, 3rd year Aeronautics and Astronautics student
List the names and posts of those assisting in compiling this risk assessment	T Glyn Thomas, Supervisor
Name, post and where required, signature of the responsible manager/supervisor approving the risk assessment	T Glyn Thomas, Supervisor
Reference number and version number of risk assessment	1

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FIGURE B.1: Section A

Assessment

Title of risk assessment	Smart wing project

Risk Acceptability	
1-3	Risk acceptable
4-6	Risk to be reduced if readily possible
7-14	Risk to be reduced if reasonably practicable
15-25	Risk unacceptable

Risk Matrix		Severity			
		very low	low	medium	high
		1	2	3	4
Likelihood: certainty	5	5	10	15	20
likely	4	4	8	12	16
possible	3	3	6	9	12
less likely	2	2	4	6	8
improbable	1	1	2	3	4

ref	Task/Aspect of work	Hazard	Harm and how it could arise	Who could be affected?	Existing measures to control
	Use of laser cutter	Fume inhalation could be hazardous	Shortly after the wood is cut, the laser cutter is filled with fumes. This could be harmful if inhaled	People in the workshop	Make sure the extractor fans are o lift the lid too early. Wait for the fum clear before taking out the laser cu
	Operation of Boldrewood wind tunnel	Risk of injury from parts breaking in the tunnel	The aerodynamic forces on the parts could cause the rig to fail and the wing could fly out of the tunnel potentially causing bodily harm	People in the vicinity of wind tunnel	Request induction and supervision lab technician before operating the tunnel. Fasten the parts in the wind securely. Use nuts, bolts, adhesive make sure the structure will not fail using the wind tunnel.
	Motors, servos, electromechanical devices.	Risk of injury from sudden or unexpected movement.	Risk of injury from sudden or unexpected movement of device or attached parts.	Person working with the device.	Do not apply power unless you've that it is safe to do so, remove pow when not in use.

	Construction and use of light tools.	Cuts and scrapes.	Cuts and scrapes from sharp edges and blades.	Person using the tools.	Follow correct operating procedures and guidelines for good practice. Don't use power tools unless you've been shown and/or trained, for example attended a workshop course.	2	3	
	Battery use and storage (particularly LiPos)	Stored energy	Heat from uncontrolled release of stored energy. Burns, fire, hot splashes.	Anyone close to the battery.	Follow manufacturer guidelines on charging, storage, and discharging. For LiPos: always charge using balancer, do not charge unattended, take special care to avoid shorts between terminals, avoid overheating, do not over-discharge.	1	4	
	Lifting and manual handling	Lifting and manual handling	Injury to arms, legs, and joints from lifting, lowering, pushing, pulling and carrying.	Person lifting	Follow general guidelines on good handling techniques for lifting, see, for example, hse.gov.uk. Light lifting: adopt a stable posture, get good hold, don't flex the back, keep load close to body, avoid twisting, keep within safe/comfortable limits. Heavier Lifting: avoid, or use appropriate and suitable lifting aids. Seek advice.	1	3	
	Soldering light electronics	Heat, smoke, solder and flux splashes.	Burns, smoke inhalation, splashes to eyes.	Person soldering	Use work holding clips and clamps as necessary, use eye protection, and ensure adequate ventilation.	2	2	

Post Risk Assessment Actions

Title of risk assessment Smart wing project

Have any of the specialist control measures listed below been identified as required during this risk assessment? - indicate yes or no - if yes then include details on the post assessment action list below.
is any exposure monitoring required?
Is any occupational health monitoring required?
Are there any hazards or other factors that could affect pregnant or nursing mothers?

Is any specific training required before people can carry out this work?

Are any additional procedures or risk assessments required as a result of this assessment?

Are any specialist disposal arrangements required?

Are any special emergency arrangements required?

	Post Assessment actions
ref	**action**

Appendix C

Method Statement

This method statement is in reference to the project "Active Control of Wing Lift: Suppressing SPOs". The scope of the work to be done is as follows: analysis of SPOs, design of controller, design of wing and the rig, building the wing, the rig and the gust generator and then finally testing the controller in a wind tunnel.

Most of the risk arises from manufacturing the parts and testing the controller in the wind tunnel. The wing will be split into four parts: the central section, the two ends of the wing and the movable trailing edge flap. The central section of the wing has pressure tappings which complicate the geometry of the part. 3D printing will therefore be necessary to produce this part. The ends of the wing are the same profile as the 3D printed parts. Due to the simple geometry of the part, the same profile can be laser cut several times and the laser cut parts can be stuck together side to side in order to extend the span of the wing. The flap will also be made similarly since all features of the flap are two dimensional. A RC servo will actuate the flap. The wing will be mounted using some fixtures on the left and right walls of the wind tunnel. These are circular discs with holes in them for the carbon fibre rods and some more holes for the PVC tubes connected to the pressure tappings of the wing. These fixtures will be made exclusively by laser cutting.

The gust generator consists of two NACA0015 flaps which are 250mm in chord and 500mm in span. Due to the simple geometry, these can be foam cut. Laser cutting will be very inconvenient for this part due to the size of the flaps. The gust generator will operate by using two RC servos to deflect the flaps. Some carbon fibre rods will be used to provide structural support to the flaps. The rods will also serve as a shaft to connect the flap to the RC servos. The rods will be supported by a stand on either side of the flap as outlined in the diagram. These stands will be laser cut out of MDF.

Once the wing and gust generator is manufactured and mounted, the electronics need to be built. I will have to solder some differential pressure sensors onto a breadboard. These will be connected to a Raspberry Pi 3 (a microcontroller). The Raspberry Pi 3 will be connected to my laptop via WiFi through the Secure Shell protocol. This will allow me to monitor the data for my test. The Raspberry Pi will be running a code to implement my controller. It will use the pressure data to estimate the lift and remove the error by adjusting the flap angle through the RC servo mentioned above. The entire setup is outlined in the diagram on the next page.

The project will finish after testing the wing in the wind tunnel. I will use the Boldrewood wing tunnel (600mm by 400mm). I will firstly request induction and supervision from the lab supervisor. When testing, the wind tunnel will be turned on and the gust generator will be programmed to produce an impulsive gust by deflecting the flaps very quickly. The system should attempt to correct the lift change caused by the gust by moving the flap.

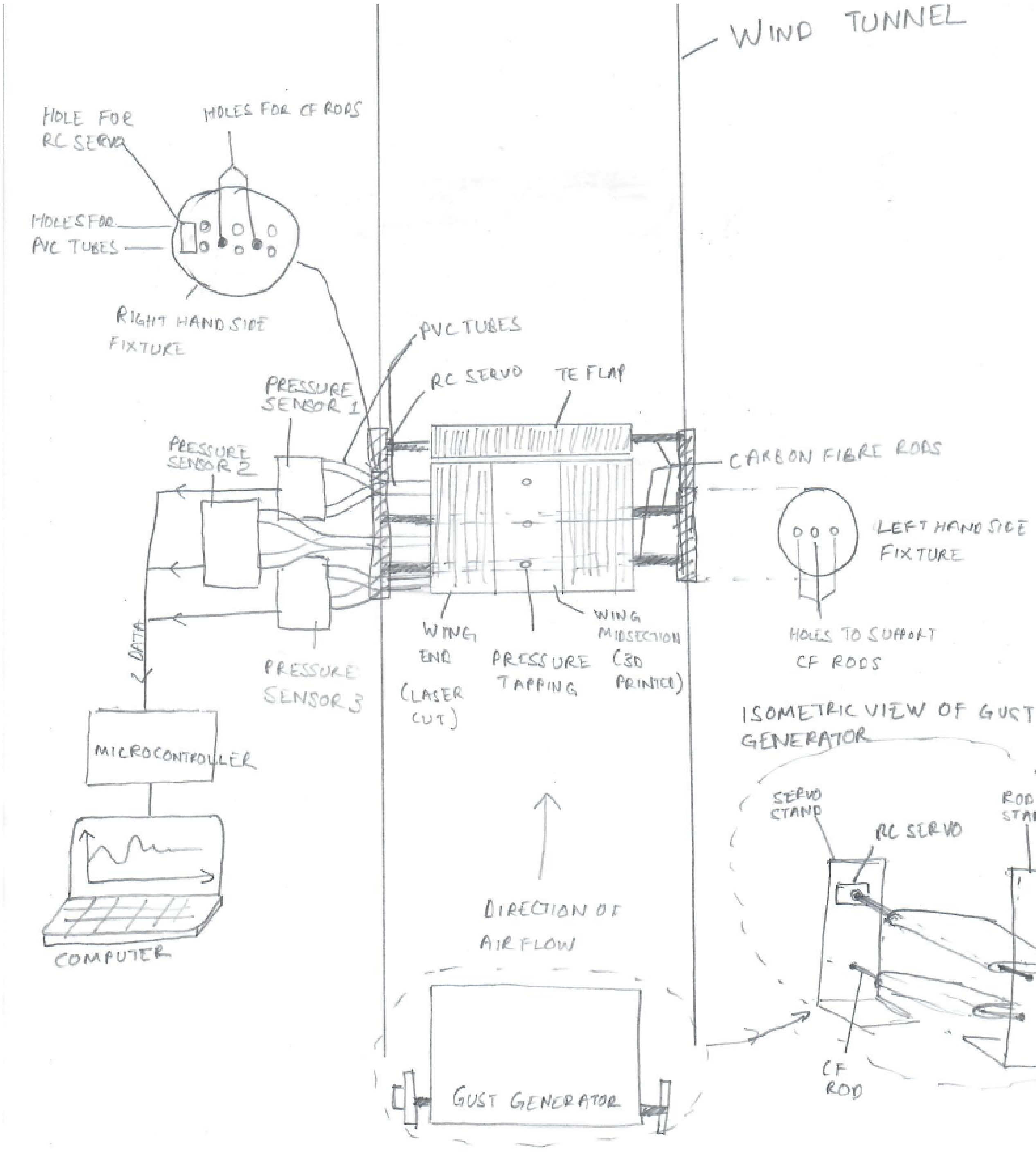

FIGURE C.1: Diagram of the setup

Appendix D

Lift Estimator

TABLE D.1: Lift estimator values and xfoil predicted values

delta	alpha	Cp1	Cp2	Cp3	p1	p2	p3	Cl	Actual Lift	Estimated Lift	Error^2	%Error
0	-5	-0.5629	-0.1619	-0.0523	-137.911	-39.6655	-12.8135	-0.3757	-2.485256	-2.328769747	0.024488	6.296565995
0	-4.5	-0.4513	-0.101	-0.0122	-110.569	-24.745	-2.989	-0.3034	-2.006991	-1.84326134	0.026807	8.157966835
0	-4	-0.3476	-0.0319	0.0351	-85.162	-7.8155	8.5995	-0.223	-1.475145	-1.399489283	0.005724	5.128696979
0	-3.5	-0.3279	0.0311	0.0736	-80.3355	7.6195	18.032	-0.1551	-1.025987	-1.409230972	0.146876	37.35375389
0	-3	-0.2003	0.0998	0.1116	-49.0735	24.451	27.342	-0.0901	-0.596012	-0.897299727	0.090775	50.55074051
0	-2.5	-0.099	0.0947	0.1499	-24.255	23.2015	36.7255	-0.0306	-0.202419	-0.111006851	0.008356	45.15986598
0	-2	-0.01	0.1603	0.1742	-2.45	39.2735	42.679	0.020367	0.1347255	0.134704751	4.31E-10	0.01540107
0	-1.5	0.0744	0.2118	0.1779	18.228	51.891	43.5855	0.071333	0.47187	0.307820941	0.026912	34.76573182
0	-1	0.1557	0.2578	0.2125	38.1465	63.161	52.0625	0.1223	0.8090145	0.685646144	0.01522	15.24921447
0	-0.5	0.2402	0.3048	0.2465	58.849	74.676	60.3925	0.1734	1.147041	1.070744217	0.005821	6.651617747
0	0	0.3389	0.3626	0.2914	83.0305	88.837	71.393	0.2391	1.5816465	1.536447515	0.002043	2.857717242
0	0.5	0.4536	0.4322	0.3497	111.132	105.889	85.6765	0.3213	2.1253995	2.101900546	0.000552	1.105625287
0	1	0.5769	0.5086	0.417	141.3405	124.607	102.165	0.413	2.731995	2.729507842	6.19E-06	0.091038158
0	1.5	0.6637	0.5559	0.458	162.6065	136.1955	112.21	0.4685	3.0991275	3.167909238	0.004731	2.219390401
0	2	0.7423	0.5977	0.4959	181.8635	146.4365	121.4955	0.516	3.41334	3.575360908	0.026251	4.746697009
0	2.5	0.8211	0.641	0.5364	201.1695	157.045	131.418	0.5634	3.726891	3.991559243	0.070049	7.101582601
0	3	0.9001	0.6867	0.5217	220.5245	168.2415	127.8165	0.6109	4.0411035	4.055605192	0.00021	0.358854756
0	3.5	0.9791	0.7356	0.4583	239.8795	180.222	112.2835	0.6584	4.355316	3.802069646	0.306082	12.70278331
0	4	1.0583	0.7882	0.4727	259.2835	193.109	115.8115	0.7058	4.668867	4.008183434	0.436503	14.15083286
0	4.5	1.1376	0.8446	0.5056	278.712	206.927	123.872	0.753	4.981095	4.307719099	0.453435	13.51863196
0	5	1.2175	0.9047	0.5365	298.2875	221.6515	131.4425	0.8004	5.294646	4.577571966	0.514195	13.54338013
0	5.5	1.2981	0.9683	0.5642	318.0345	237.2335	138.229	0.8474	5.605551	4.811974158	0.629764	14.15698193
0	6	1.3801	0.9185	0.5891	338.1245	225.0325	144.3295	0.894	5.91381	5.663436156	0.062687	4.233714715
0	6.5	1.4644	0.9275	0.6113	358.778	227.2375	149.7685	0.9388	6.210162	6.184974825	0.000634	0.405579992
0	7	1.5562	0.9788	0.6301	381.269	239.806	154.3745	0.9809	6.4886535	6.490330372	2.81E-06	0.025843141
0	7.5	1.6219	1.0202	0.6452	397.3655	249.949	158.074	1.02	6.7473	6.693090432	0.002939	0.803426084
0	8	1.6171	1.0535	0.6567	396.1895	258.1075	160.8915	1.0566	6.989409	6.555015548	0.188698	6.215024075
0	8.5	1.6936	1.0822	0.6655	414.932	265.139	163.0475	1.0912	7.218288	6.844889064	0.139427	5.172957019
0	8	1.7583	1.1083	0.6721	430.7835	271.5335	164.6645	1.1245	7.4385675	7.07475877	0.132357	4.890843973
0	9.5	1.8145	1.1292	0.6737	444.5525	276.654	165.0565	1.1531	7.6277565	7.2587733	0.136149	4.83737519
0	10	2.1254	1.7566	1.7207	520.723	430.367	421.5715	1.1817	7.8169455	11.83941768	16.18028	51.45836292
15	-5	0.4177	0.6491	0.7953	102.3365	159.0295	194.8485	0.728	4.81572	3.461323619	1.83439	28.12448358
15	-4.5	0.5579	0.7427	0.8796	136.6855	181.9615	215.502	0.7856	5.196744	4.185627561	1.022356	19.45672981
15	-4	0.7666	0.895	1.0023	187.817	219.275	245.5635	0.8432	5.577768	5.174937811	0.162272	7.222067849
15	-3.5	0.8569	0.9405	1.0341	209.9405	230.4225	253.3545	0.9008	5.958792	5.584684986	0.139956	6.278235821
15	-3	0.9472	0.9832	1.0652	232.064	240.884	260.974	0.9584	6.339816	6.005605243	0.111697	5.271616034
15	-2.5	1.0045	1.0116	1.0731	246.1025	247.842	262.9095	0.9841	6.5098215	6.192611228	0.100622	4.872795232
15	-2	1.0338	1.015	1.0337	253.281	248.675	253.2565	0.9804	6.485346	6.082245906	0.16249	6.215552625
15	-1.5	1.0824	1.0342	1.0464	265.188	253.379	256.368	0.9971	6.5958165	6.304831666	0.084672	4.411657513
15	-1	1.1377	1.0599	1.056	278.7365	259.6755	258.72	1.021	6.753915	6.506925645	0.061004	3.656980506
15	-0.5	1.2023	1.0984	1.0691	294.5635	269.108	261.9295	1.054	6.97221	6.707735617	0.069947	3.793264739
15	0	1.2673	1.0869	1.0566	310.4885	266.2905	258.867	1.0864	7.186536	7.02945959	0.024673	2.185704068
15	0.5	1.3339	1.1346	1.0581	326.8055	277.977	259.2345	1.1218	7.420707	7.118275142	0.091465	4.075512722
15	1	1.4024	1.1728	1.0755	343.588	287.336	263.4975	1.1583	7.6621545	7.367328922	0.086922	3.847815625
15	1.5	1.4771	1.2083	1.0918	361.8895	296.0335	267.491	1.1952	7.906248	7.656503396	0.062372	3.158825831
15	2	1.5129	1.2449	1.1099	370.6605	305.0005	271.9255	1.2352	8.170848	7.75013252	0.177002	5.148981838
15	2.5	1.6046	1.2801	1.1276	393.127	313.6245	276.262	1.2757	8.4387555	8.137229375	0.090918	3.573111281
15	3	1.6818	1.3176	1.1455	412.041	322.812	280.6475	1.3177	8.7165855	8.438085282	0.077562	3.195060935
15	3.5	1.7543	1.3546	1.1633	429.8035	331.877	285.0085	1.3601	8.9970615	8.71685976	0.078513	3.114369503
15	4	1.8288	1.3906	1.1802	448.056	340.697	289.149	1.4026	9.278199	9.00593292	0.074129	2.934471232
15	4.5	1.9024	1.4263	1.1967	466.088	349.4435	293.1915	1.4451	9.5593365	9.289562006	0.072778	2.822104797
15	5	1.9747	1.462	1.2116	483.8015	358.19	296.842	1.4869	9.8358435	9.556636504	0.077957	2.838668554
15	5.5	2.0451	1.4971	1.2259	501.0495	366.7895	300.3455	1.5279	10.107059	9.813538877	0.086154	2.904105316
15	6	2.1167	1.5305	1.2389	518.5915	374.9725	303.5305	1.5684	10.374966	10.07802334	0.088175	2.862107318
15	6.5	2.1844	1.5625	1.2505	535.178	382.8125	306.3725	1.6073	10.63229	10.32152241	0.096576	2.92286142
15	7	2.2507	1.5934	1.2605	551.4215	390.383	308.8225	1.6454	10.884321	10.55403418	0.109089	3.034519299
15	7.5	2.3164	1.6236	1.2693	567.518	397.782	310.9785	1.6822	11.127753	10.77993418	0.120978	3.125687794
15	8	2.3806	1.6513	1.2764	583.247	404.5685	312.718	1.7176	11.361924	11.00145733	0.129936	3.172584742
15	8.5	2.4403	1.6774	1.2811	597.8735	410.963	313.8695	1.7509	11.582204	11.19384998	0.150818	3.353019353
15	9	2.4986	1.7021	1.2838	612.157	417.0145	314.531	1.7829	11.793884	11.37445113	0.175924	3.556355003
15	9.5	2.5559	1.7243	1.2848	626.1955	422.4535	314.776	1.8135	11.996303	11.55325316	0.196293	3.693215816
15	10	2.6103	1.7441	1.2826	639.5235	427.3045	314.237	1.8412	12.179538	11.71067099	0.219836	3.849628825
30	-5	1.6576	1.6272	1.8181	406.112	398.664	445.4345	0.9964	6.591186	10.74303655	17.23786	62.9909481
30	-4.5	1.5026	1.4945	1.6624	368.137	366.1525	407.288	1.0399	6.8789385	9.718980337	8.065838	41.2860478
30	-4	1.4287	1.4285	1.5911	350.0315	349.9825	389.8195	1.0834	7.166691	9.263910112	4.398328	29.26342313

30	-3.5	1.1681	1.1739	1.2518	286.1845	287.6055	306.691	1.1269	7.4544435	7.238950837	0.046437	2.890794777
30	-3	1.2413	1.2164	1.2848	304.1185	298.018	314.776	1.1704	7.742196	7.584518907	0.024862	2.036593916
30	-2.5	1.3197	1.2644	1.3101	323.3265	309.778	320.9745	1.2139	8.0299485	7.879065893	0.022766	1.878998444
30	-2	1.4016	1.3162	1.3359	343.392	322.469	327.2955	1.2634	8.357391	8.173722429	0.033734	2.197678335
30	-1.5	1.4808	1.3268	1.358	362.796	325.066	332.71	1.3091	8.6596965	8.659504826	3.67E-08	0.002213403
30	-1	1.558	1.3779	1.3793	381.71	337.5855	337.9285	1.353	8.950095	8.906091479	0.001936	0.491654229
30	-0.5	1.6451	1.4207	1.4018	403.0495	348.0715	343.441	1.398	9.24777	9.257004064	8.53E-05	0.099851789
30	0	1.6922	1.4636	1.424	414.589	358.582	348.88	1.4433	9.5474295	9.399298728	0.021943	1.551525174
30	0.5	1.7804	1.5014	1.4443	436.198	367.843	353.8535	1.4861	9.8305515	9.769984295	0.003668	0.616111975
30	1	1.856	1.54	1.4631	454.72	377.3	358.4595	1.5282	10.109043	10.06205071	0.002208	0.464853965
30	1.5	1.9291	1.5774	1.4778	472.6295	386.463	362.061	1.5701	10.386212	10.32261727	0.004044	0.612294813
30	2	2.0044	1.6137	1.4835	491.078	395.3565	363.4575	1.6116	10.660734	10.5451882	0.013351	1.08384468
30	2.5	2.0787	1.6495	1.467	509.2815	404.1275	359.415	1.6526	10.931949	10.62866494	0.091981	2.774290851
30	3	2.1499	1.6842	1.4779	526.7255	412.629	362.0855	1.6925	11.195888	10.870967	0.105573	2.902141511
30	3.5	2.2209	1.7179	1.493	544.1205	420.8855	365.785	1.7315	11.453873	11.14363068	0.09625	2.708619499
30	4	2.2893	1.7496	1.5061	560.8785	428.652	368.9945	1.7692	11.703258	11.40163424	0.090977	2.577263144
30	4.5	2.3546	1.7811	1.5179	576.877	436.3695	371.8855	1.8057	11.944706	11.63675675	0.094832	2.578119246
30	5	2.421	1.81	1.5278	593.145	443.45	374.311	1.8409	12.177554	11.88022796	0.088402	2.441586801
30	5.5	2.4823	1.8377	1.5357	608.1635	450.2365	376.2465	1.8746	12.400479	12.09172659	0.095328	2.489842574
30	6	2.5465	1.863	1.5406	623.8925	456.435	377.447	1.906	12.60819	12.31297415	0.087152	2.341460955
30	6.5	2.6051	1.8871	1.5447	638.2495	462.3395	378.4515	1.9371	12.813917	12.5070608	0.09416	2.394706545
30	7	2.662	1.9092	1.5449	652.19	467.754	378.5005	1.9654	13.001121	12.67942738	0.103487	2.474352964
30	7.5	2.7149	1.9276	1.5407	665.1505	472.262	377.4715	1.9903	13.165835	12.82453819	0.116483	2.592287748
30	8	2.7652	1.9429	1.5336	677.474	476.0105	375.732	2.0132	13.317318	12.95552967	0.130891	2.716675588
30	8.5	2.8135	1.9586	1.5265	689.3075	479.857	373.9925	2.0367	13.472771	13.07399834	0.159019	2.959837814
30	9	2.8571	1.969	1.5121	699.9895	482.405	370.4645	2.055	13.593825	13.1525925	0.194686	3.245830361
30	9.5	2.8951	1.975	1.4924	709.2995	483.875	365.638	2.0698	13.691727	13.19401104	0.247721	3.635158396
30	10	2.935	1.982	1.474	719.075	485.59	361.13	2.0867	13.803521	13.24770024	0.308936	4.02665584
45	-5	2.0434	1.952	2.1479	500.633	478.24	526.2355	1.3171	8.7126165	12.96676264	18.09776	48.82742333
45	-4.5	1.9784	1.8978	2.0908	484.708	464.961	512.246	1.3595	8.9930925	12.57976479	12.86422	39.88252412
45	-4	1.9245	1.8549	2.0427	471.5025	454.4505	500.4615	1.4019	9.2735685	12.2429255	8.817081	32.01957266
45	-3.5	1.888	1.8055	1.9825	462.56	442.3475	485.7125	1.4443	9.5540445	11.95722519	5.775277	25.15354293
45	-3	1.834	1.7343	1.8848	449.33	424.9035	461.776	1.4867	9.8345205	11.47093685	2.677858	16.63951334
45	-2.5	1.7773	1.6115	1.6686	435.4385	394.8175	408.807	1.5291	10.114997	10.52636661	0.169225	4.066932771
45	-2	1.8208	1.6509	1.6843	446.096	404.4705	412.6535	1.5715	10.395473	10.62943028	0.054736	2.250573832
45	-1.5	1.9057	1.6898	1.6993	466.8965	414.001	416.3285	1.6134	10.672641	10.94438361	0.073844	2.546160874
45	-1	1.9805	1.7271	1.7121	485.2225	423.1395	419.4645	1.6533	10.93658	11.20256753	0.07075	2.432095241
45	-0.5	2.053	1.7623	1.7236	502.985	431.7635	422.282	1.6921	11.193242	11.45250144	0.067216	2.316218554
45	0	2.1234	1.7959	1.7339	520.233	439.9955	424.8055	1.7298	11.442627	11.69306728	0.06272	2.188660691
45	0.5	2.1931	1.8287	1.7432	537.3095	448.0315	427.084	1.7667	11.686721	11.92829036	0.058356	2.067045792
45	1	2.2619	1.8599	1.7518	554.1655	455.6755	429.191	1.8024	11.922876	12.16341082	0.057857	2.01742285
45	1.5	2.3277	1.8892	1.7583	570.2865	462.854	430.7835	1.8368	12.150432	12.38064024	0.052996	1.894650634
45	2	2.3917	1.9186	1.7633	585.9665	470.057	432.0085	1.8696	12.367404	12.57880014	0.044688	1.709300821
45	2.5	2.4531	1.9445	1.7658	601.0095	476.4025	432.621	1.9004	12.571146	12.76751578	0.038561	1.562067492
45	3	2.5151	1.9691	1.767	616.1995	482.4295	432.915	1.9301	12.767612	12.95850832	0.036442	1.495164698
45	3.5	2.5735	1.9917	1.7668	630.5075	487.9665	432.866	1.9583	12.954155	13.13338	0.032122	1.383536867
45	4	2.63	2.0135	1.764	644.35	493.3075	432.18	1.9851	13.131437	13.28686988	0.02416	1.183673882
45	4.5	2.6848	2.0334	1.7597	657.776	498.183	431.1265	2.0104	13.298796	13.43286548	0.017975	1.008132482
45	5	2.7338	2.0494	1.7494	669.781	502.103	428.603	2.0317	13.439696	13.53357897	0.008814	0.698553577
45	5.5	2.7862	2.0646	1.7386	682.619	505.827	425.957	2.0538	13.585887	13.65316592	0.004526	0.495211849
45	6	2.8305	2.0742	1.7189	693.4725	508.179	421.1305	2.0706	13.697019	13.7071563	0.000103	0.074010968
45	6.5	2.8754	2.0863	1.6969	704.473	511.1435	415.7405	2.0896	13.822704	13.73625234	0.007474	0.625432367
45	7	2.9151	2.0924	1.6674	714.1995	512.638	408.513	2.104	13.91796	13.72553546	0.037027	1.382562786
45	7.5	2.9506	2.0948	1.6262	722.897	513.226	398.419	2.1152	13.992048	13.64157963	0.122828	2.504768216
45	8	2.9859	2.0968	1.5853	731.5455	513.716	388.3985	2.1275	14.073413	13.56065199	0.262923	3.643469634
45	8.5	3.0167	2.0946	1.5436	739.0915	513.177	378.182	2.1367	14.134271	13.47482395	0.43487	4.665586039
45	9	3.038	2.0853	1.4983	744.31	510.8985	367.0835	2.1408	14.161392	13.35711295	0.646865	5.679378512
45	9.5	3.0624	2.0738	1.4491	750.288	508.081	355.0295	2.1453	14.19116	13.24353395	0.897994	6.677576647
45	10	3.0852	2.0613	1.3962	755.874	505.0185	342.069	2.1502	14.223573	13.10445214	1.252431	7.86807126
60	-5	2.8981	2.6236	2.7989	710.0345	642.782	685.7305	1.5257	10.092506	17.66801805	57.38839	75.06077212
60	-4.5	2.0694	1.9289	2.0895	507.003	472.5805	511.9275	1.5613	10.328	12.86892654	6.45631	24.60231568
60	-4	2.0209	1.8818	2.031	495.1205	461.041	497.595	1.5969	10.563494	12.51911061	3.824438	18.51297686
60	-3.5	1.9676	1.8034	1.9045	482.062	441.833	466.6025	1.6325	10.798988	11.89890063	1.209809	10.1853357
60	-3	2.0345	1.8354	1.9131	498.4525	449.673	468.7095	1.6681	11.034482	12.11980188	1.17792	9.83571707
60	-2.5	2.104	1.87	1.9244	515.48	458.15	471.478	1.7037	11.269976	12.35635581	1.180222	9.639597786
60	-2	2.1718	1.904	1.9321	532.091	466.48	473.3645	1.7384	11.499516	12.56529523	1.135885	9.268035546
60	-1.5	2.2379	1.936	1.9377	548.2855	474.32	474.7365	1.7721	11.722442	12.76359866	1.084008	8.881743276
60	-1	2.3036	1.9658	1.9405	564.382	481.621	475.4225	1.8029	11.926184	12.95476366	1.057977	8.624554202
60	-0.5	2.3633	1.9935	1.9401	579.0085	488.4075	475.3245	1.8328	12.123972	13.10690366	0.966155	8.107340199
60	0	2.4253	2.0194	1.9376	594.1985	494.753	474.712	1.8645	12.333668	13.26792345	0.872834	7.574843
60	0.5	2.485	2.0432	1.9348	608.825	500.584	474.026	1.8926	12.519549	13.42685105	0.823197	7.247082566
60	1	2.5439	2.0664	1.9303	623.2555	506.268	472.9235	1.9198	12.699477	13.57450391	0.765672	6.89025942
60	1.5	2.5991	2.0871	1.9226	636.7795	511.3395	471.037	1.9463	12.874775	13.69720121	0.676386	6.38789216
60	2	2.6515	2.1055	1.9118	649.6175	515.8475	468.391	1.9693	13.02692	13.79909266	0.596251	5.927519278
60	2.5	2.7039	2.1223	1.9	662.4555	519.9635	465.5	1.9915	13.173773	13.90367404	0.532756	5.540565866
60	3	2.7536	2.138	1.8838	674.632	523.81	461.531	2.0136	13.319964	13.97332414	0.426879	4.905119384
60	3.5	2.8005	2.1498	1.8686	686.1225	526.701	457.807	2.0317	13.439696	14.05626321	0.380156	4.587661277
60	4	2.8472	2.1607	1.8466	697.564	529.3715	452.417	2.0504	13.563396	14.10127485	0.289314	3.965664994
60	4.5	2.8864	2.1679	1.8244	707.168	531.1355	446.978	2.0652	13.661298	14.12684954	0.216738	3.407813381
60	5	2.9289	2.175	1.796	717.5805	532.875	440.02	2.081	13.765815	14.13181167	0.133954	2.658735901
60	5.5	2.9654	2.1775	1.7661	726.523	533.4875	432.6945	2.0929	13.844534	14.12204169	0.077011	2.004460388
60	6	2.9975	2.176	1.7282	734.3875	533.12	423.409	2.1026	13.908699	14.06244456	0.023638	1.105391387
60	6.5	3.0307	2.1759	1.6877	742.5215	533.0955	413.4865	2.1138	13.982787	13.9847663	3.92E-06	0.014155228
60	7	3.0584	2.1706	1.6434	749.308	531.797	402.633	2.122	14.03703	13.88408856	0.023391	1.089556968
60	7.5	3.0848	2.1614	1.59	755.776	529.543	389.55	2.1282	14.078043	13.74223895	0.112764	2.385303502
60	8	3.102	2.1449	1.5254	759.99	525.5005	373.723	2.1306	14.093919	13.52435951	0.324398	4.041171851
60	8.5	3.1239	2.1291	1.4662	765.3555	521.6295	359.219	2.1348	14.121702	13.360092	0.58005	5.393188429
60	9	3.1387	2.1082	1.404	768.9815	516.509	343.98	2.1372	14.137578	13.16894959	0.938241	6.851445182

60	9.5	3.1515	2.0817	1.344	772.1175	510.0165	329.28	2.1387	14.147501	13.01201063	1.289337	8.026081125
60	10	3.1578	2.047	1.3008	773.661	501.515	318.696	2.1367	14.134271	12.97035745	1.354694	8.234687791
-15	-5	-1.5325	-0.9498	-0.8876	-375.463	-232.701	-217.462	-1.2972	-8.580978	-8.114151402	0.217927	5.440249328
-15	-4.5	-1.4534	-0.9063	-0.8626	-356.083	-222.044	-211.337	-1.245	-8.235675	-7.792958666	0.195998	5.375592573
-15	-4	-1.3735	-0.8624	-0.8371	-336.508	-211.288	-205.09	-1.1924	-7.887726	-7.466774604	0.1772	5.336790298
-15	-3.5	-1.2929	-0.8183	-0.8121	-316.761	-200.484	-198.965	-1.1396	-7.538454	-7.141166614	0.157837	5.270144062
-15	-3	-1.212	-0.7733	-0.7867	-296.94	-189.459	-192.742	-1.0865	-7.187198	-6.816525721	0.137398	5.157389638
-15	-2.5	-1.131	-0.7287	-0.761	-277.095	-178.532	-186.445	-1.0333	-6.83528	-6.48731	0.121083	5.090786709
-15	-2	-1.0478	-0.6837	-0.7353	-256.711	-167.507	-180.149	-0.9798	-6.481377	-6.148964248	0.110498	5.128736564
-15	-1.5	-0.9662	-0.6381	-0.7095	-236.719	-156.335	-173.828	-0.9263	-6.127475	-5.821569323	0.093578	4.99235333
-15	-1	-0.8834	-0.5924	-0.6832	-216.433	-145.138	-167.384	-0.8724	-5.770926	-5.485461942	0.08149	4.94659016
-15	-0.5	-0.8007	-0.5459	-0.6569	-196.172	-133.746	-160.941	-0.8186	-5.415039	-5.15429398	0.067988	4.815201153
-15	0	-0.7158	-0.4991	-0.6304	-175.371	-122.28	-154.448	-0.7645	-5.057168	-4.812211437	0.060003	4.843740345
-15	0.5	-0.633	-0.4481	-0.6039	-155.085	-109.785	-147.956	-0.7105	-4.699958	-4.504180656	0.038329	4.165502441
-15	1	-0.5488	-0.4199	-0.5768	-134.456	-102.876	-141.316	-0.6558	-4.338117	-4.059157164	0.077819	6.430435974
-15	1.5	-0.463	-0.3702	-0.5498	-113.435	-90.699	-134.701	-0.601	-3.975615	-3.725392356	0.062611	6.293935496
-15	2	-0.379	-0.3189	-0.5225	-92.855	-78.1305	-128.013	-0.5461	-3.612452	-3.407907741	0.041838	5.662187002
-15	2.5	-0.2943	-0.2702	-0.4952	-72.1035	-66.199	-121.324	-0.4914	-3.250611	-3.072436728	0.031746	5.481254823
-15	3	-0.2083	-0.2228	-0.4677	-51.0335	-54.586	-114.587	-0.4362	-2.885463	-2.721843284	0.026771	5.670483948
-15	3.5	-0.1226	-0.1757	-0.4404	-30.037	-43.0465	-107.898	-0.3812	-2.521638	-2.372369084	0.022281	5.919522005
-15	4	-0.0371	-0.1276	-0.4126	-9.0895	-31.262	-101.087	-0.3258	-2.155167	-2.026376902	0.016587	5.975875558
-15	4.5	0.0487	-0.08	-0.3853	11.9315	-19.6	-94.3985	-0.2707	-1.790681	-1.679152079	0.012439	6.228270255
-15	5	0.1348	-0.0325	-0.3572	33.026	-7.9625	-87.514	-0.2149	-1.421564	-1.324901381	0.009344	6.799704605
-15	5.5	0.2346	0.0157	-0.3291	57.477	3.8465	-80.6295	-0.1588	-1.050462	-0.903892049	0.021483	13.95290371
-15	6	0.2959	0.0635	-0.3007	72.4955	15.5575	-73.6715	-0.1024	-0.677376	-0.677307862	4.64E-09	0.010059167
-15	6.5	0.3864	0.1113	-0.2729	94.668	27.2685	-66.8605	-0.0461	-0.304952	-0.303879529	1.15E-06	0.351521911
-15	7	0.4761	0.1578	-0.2443	116.6445	38.661	-59.8535	0.0102	0.067473	0.077539506	0.000101	14.91930995
-15	7.5	0.5618	0.2072	-0.2165	137.641	50.764	-53.0425	0.066	0.43659	0.417373981	0.000369	4.401387826
-15	8	0.6458	0.2619	-0.188	158.221	64.1655	-46.06	0.12255	0.8106683	0.723446521	0.007608	10.75923827
-15	8.5	0.7319	0.3011	-0.1599	179.3155	73.7695	-39.1755	0.1791	1.1847465	1.123594909	0.00374	5.161576015
-15	9	0.816	0.3466	-0.1312	199.92	84.917	-32.144	0.23565	1.5588248	1.482289105	0.005858	4.909829955
-15	9.5	0.9018	0.394	-0.1008	220.941	96.53	-24.696	0.2922	1.932903	1.849709149	0.006921	4.304088231
-15	10	0.9354	0.4119	-0.0862	229.173	100.9155	-21.119	0.34875	2.3069813	2.013851972	0.085925	12.7061838
-30	-5	-2.0184	-1.3441	-1.3023	-494.508	-329.305	-319.064	-1.7167	-11.35597	-10.99241219	0.132175	3.201472836
-30	-4.5	-1.9454	-1.3052	-1.2828	-476.623	-319.774	-314.286	-1.6698	-11.04573	-10.71109839	0.111976	3.029484696
-30	-4	-1.872	-1.2659	-1.263	-458.64	-310.146	-309.435	-1.6229	-10.73548	-10.42808701	0.094493	2.863368877
-30	-3.5	-1.7979	-1.2275	-1.2431	-440.486	-300.738	-304.56	-1.5757	-10.42326	-10.13587417	0.082588	2.757116773
-30	-3	-1.7215	-1.1858	-1.2216	-421.768	-290.521	-299.292	-1.5269	-10.10044	-9.840199792	0.067727	2.576557236
-30	-2.5	-1.6461	-1.145	-1.1999	-403.295	-280.525	-293.976	-1.4782	-9.778293	-9.543472427	0.055141	2.401447502
-30	-2	-1.5689	-1.1042	-1.1786	-384.381	-270.529	-288.757	-1.4299	-9.458789	-9.2399284	0.0479	2.313828036
-30	-1.5	-1.4924	-1.0634	-1.1573	-365.638	-260.533	-283.539	-1.3818	-9.140607	-8.93999318	0.040246	2.194753801
-30	-1	-1.415	-1.0218	-1.1361	-346.675	-250.341	-278.345	-1.3335	-8.821103	-8.640457721	0.032633	2.047870759
-30	-0.5	-1.339	-0.9805	-1.1145	-328.055	-240.223	-273.053	-1.285	-8.500275	-8.344017796	0.024416	1.838260577
-30	0	-1.2584	-0.9372	-1.0908	-308.308	-229.614	-267.246	-1.2347	-8.167541	-8.021991103	0.021185	1.78204684
-30	0.5	-1.1805	-0.8949	-1.0677	-289.223	-219.251	-261.587	-1.1852	-7.840098	-7.712048949	0.016397	1.633258301
-30	1	-1.1016	-0.8513	-1.0457	-269.892	-208.569	-256.197	-1.1363	-7.516625	-7.410913755	0.011175	1.406359259
-30	1.5	-1.0242	-0.8036	-1.0235	-250.929	-196.882	-250.758	-1.0874	-7.193151	-7.13895251	0.002937	0.753473551
-30	2	-0.9441	-0.7787	-1.0012	-231.305	-190.782	-245.294	-1.0386	-6.870339	-6.726375394	0.020726	2.095436713
-30	2.5	-0.8656	-0.7334	-0.9789	-212.072	-179.683	-239.831	-0.9895	-6.545543	-6.434855762	0.012252	1.69102467
-30	3	-0.7838	-0.6876	-0.9546	-192.031	-168.462	-233.877	-0.9387	-6.209501	-6.116772452	0.008598	1.493325399
-30	3.5	-0.7044	-0.6417	-0.9301	-172.578	-157.217	-227.875	-0.8877	-5.872136	-5.810383617	0.003813	1.051608616
-30	4	-0.6242	-0.5986	-0.9071	-152.929	-146.657	-222.24	-0.838	-5.54337	-5.493623608	0.002475	0.897403424
-30	4.5	-0.5446	-0.5546	-0.8847	-133.427	-135.877	-216.752	-0.7887	-5.217251	-5.188628414	0.000819	0.548604782
-30	5	-0.4662	-0.5122	-0.8618	-114.219	-125.489	-211.141	-0.7393	-4.89047	-4.877893089	0.000158	0.257161622
-30	5.5	-0.3855	-0.4692	-0.8392	-94.4475	-114.954	-205.604	-0.6899	-4.563689	-4.560465505	1.04E-05	0.070622584
-30	6	-0.3047	-0.4257	-0.8158	-74.6515	-104.297	-199.871	-0.6369	-4.213094	-4.24036104	0.000744	0.647209458
-30	6.5	-0.2185	-0.3788	-0.7882	-53.5325	-92.806	-193.109	-0.5839	-3.862499	-3.885355804	0.000522	0.591775097
-30	7	-0.1375	-0.3351	-0.7649	-33.6875	-82.0995	-187.401	-0.5336	-3.529764	-3.565942001	0.001309	1.024941083
-30	7.5	-0.0659	-0.2908	-0.7422	-16.1455	-71.246	-181.839	-0.4829	-3.194384	-3.302001931	0.011582	3.368989078
-30	8	0.0194	-0.2501	-0.7204	4.753	-61.2745	-176.498	-0.4334	-2.866941	-2.953066946	0.007418	3.004105991
-30	8.5	0.0973	-0.2066	-0.6972	23.8385	-50.617	-170.814	-0.3839	-2.539499	-2.649144821	0.012022	4.317636751
-30	9	0.1794	-0.1617	-0.6737	43.953	-39.6165	-165.057	-0.32767	-2.167515	-2.32946428	0.026228	7.471656705
-30	9.5	0.2929	-0.0923	-0.6216	71.7605	-22.6135	-152.292	-0.27143	-1.795532	-1.807270314	0.000138	0.653779332
-30	10	0.3548	-0.0631	-0.6156	86.926	-15.4595	-150.822	-0.2152	-1.423548	-1.612673044	0.035768	13.28547012
-45	-5	-2.4015	-1.6613	-1.6289	-588.368	-407.019	-399.081	-2.0095	-13.29284	-13.22454036	0.004665	0.513826469
-45	-4.5	-2.3375	-1.6291	-1.618	-572.688	-399.13	-396.41	-1.9671	-13.01237	-13.00553286	4.67E-05	0.052516541
-45	-4	-2.2679	-1.5945	-1.6044	-555.636	-390.653	-393.078	-1.9247	-12.73189	-12.75430039	0.000502	0.176013838
-45	-3.5	-2.2001	-1.5597	-1.59	-539.025	-382.127	-389.55	-1.8815	-12.44612	-12.50852742	0.003894	0.501400531
-45	-3	-2.1317	-1.5237	-1.5751	-522.267	-373.307	-385.9	-1.8378	-12.15705	-12.26321809	0.011272	0.873329636
-45	-2.5	-2.0583	-1.4868	-1.5593	-504.284	-364.266	-382.029	-1.7932	-11.86202	-11.99156336	0.016783	1.092127685
-45	-2	-1.9846	-1.4473	-1.5409	-486.227	-354.589	-377.521	-1.7461	-11.55045	-11.71673529	0.02765	1.439630196
-45	-1.5	-1.9082	-1.4072	-1.5207	-467.509	-344.764	-372.572	-1.6973	-11.22764	-11.42021833	0.037087	1.715220982
-45	-1	-1.8349	-1.3676	-1.5023	-449.551	-335.062	-368.064	-1.6506	-10.91872	-11.14800239	0.052571	2.099911112
-45	-0.5	-1.7592	-1.3287	-1.4847	-431.004	-325.532	-363.752	-1.6046	-10.61443	-10.86446877	0.06252	2.355659193
-45	0	-1.6861	-1.2897	-1.4673	-413.095	-315.977	-359.489	-1.5588	-10.31146	-10.59612384	0.081032	2.760635143
-45	0.5	-1.6119	-1.2505	-1.4496	-394.916	-306.373	-355.152	-1.513	-10.0085	-10.32136655	0.097889	3.126059938
-45	1	-1.5365	-1.2104	-1.4319	-376.443	-296.548	-350.816	-1.467	-9.704205	-10.04539959	0.116414	3.515945837
-45	1.5	-1.4594	-1.1689	-1.4141	-357.553	-286.381	-346.455	-1.4208	-9.398592	-9.76779438	0.13631	3.928273298
-45	2	-1.3856	-1.1267	-1.3962	-339.472	-276.042	-342.069	-1.3744	-9.091656	-9.510457226	0.175394	4.606435025
-45	2.5	-1.3074	-1.1013	-1.378	-320.313	-269.819	-337.61	-1.3279	-8.784059	-9.135687443	0.123643	4.003035082
-45	3	-1.2317	-1.059	-1.36	-301.767	-259.455	-333.2	-1.2809	-8.473154	-8.868492156	0.156293	4.665779467
-45	3.5	-1.1537	-1.0165	-1.3416	-282.657	-249.043	-328.692	-1.2338	-8.161587	-8.588082197	0.181898	5.225640513
-45	4	-1.0774	-0.9744	-1.3227	-263.963	-238.728	-324.062	-1.1865	-7.848698	-8.311145636	0.213858	5.892036688
-45	4.5	-0.9988	-0.9324	-1.3045	-244.706	-228.438	-319.603	-1.1387	-7.532501	-8.026109057	0.243649	6.553050432
-45	5	-0.9209	-0.8907	-1.2861	-225.621	-218.222	-315.095	-1.0906	-7.214319	-7.741790767	0.278226	7.311456111
-45	5.5	-0.8416	-0.8482	-1.2669	-206.192	-207.809	-310.391	-1.042	-6.89283	-7.449752478	0.310163	8.079736153
-45	6	-0.7622	-0.8064	-1.2477	-186.739	-197.568	-305.687	-0.9929	-6.568034	-7.153327754	0.342569	8.911255617
-45	6.5	-0.6819	-0.7612	-1.2268	-167.066	-186.494	-300.566	-0.9414	-6.227361	-6.860596299	0.400987	10.16859788

-45	7	-0.5961	-0.7155	-1.2034	-146.045	-175.298	-294.833	-0.8877	-5.872136	-6.526880287	0.428691	11.15002859
-45	7.5	-0.5162	-0.6721	-1.1849	-126.469	-164.665	-290.301	-0.8374	-5.539401	-6.241036067	0.492292	12.66626243
-45	8	-0.436	-0.6292	-1.1672	-106.82	-154.154	-285.964	-0.7873	-5.20799	-5.955806554	0.55923	14.35903536
-45	8.5	-0.3552	-0.5867	-1.1506	-87.024	-143.742	-281.897	-0.73765	-4.879555	-5.672045445	0.628042	16.24104526
-45	9	-0.2762	-0.5447	-1.133	-67.669	-133.452	-277.585	-0.688	-4.55112	-5.388641384	0.701442	18.40253352
-45	9.5	-0.1912	-0.5016	-1.1151	-46.844	-122.892	-273.2	-0.6367	-4.211771	-5.078540163	0.75129	20.57969833
-45	10	-0.1036	-0.4565	-1.0963	-25.382	-111.843	-268.594	-0.5854	-3.872421	-4.760552442	0.788777	22.93478531
-60	-5	-3.9453	-2.9049	-2.9584	-966.599	-711.701	-724.808	-2.1784	-14.41012	-22.49342278	65.33985	56.09466837
-60	-4.5	-2.6361	-1.8808	-1.8588	-645.845	-460.796	-455.406	-2.1433	-14.17793	-14.63588978	0.209728	3.230092768
-60	-4	-2.5791	-1.8553	-1.8561	-631.88	-454.549	-454.745	-2.1082	-13.94574	-14.46641456	0.271099	3.733551965
-60	-3.5	-2.5185	-1.8281	-1.8521	-617.033	-447.885	-453.765	-2.0731	-13.71356	-14.27977533	0.320604	4.128898484
-60	-3	-2.458	-1.799	-1.8474	-602.21	-440.755	-452.613	-2.0365	-13.47145	-14.09984786	0.394887	4.664683276
-60	-2.5	-2.3942	-1.7698	-1.8409	-586.579	-433.601	-451.021	-1.999	-13.22339	-13.89237634	0.447549	5.059153475
-60	-2	-2.3285	-1.7381	-1.8345	-570.483	-425.835	-449.453	-1.9602	-12.96672	-13.68954988	0.522479	5.574476119
-60	-1.5	-2.2627	-1.7066	-1.8271	-554.362	-418.117	-447.64	-1.9206	-12.70477	-13.47894408	0.599347	6.093578533
-60	-1	-2.1957	-1.6729	-1.8176	-537.947	-409.861	-445.312	-1.8805	-12.43951	-13.26138597	0.675484	6.607001698
-60	-0.5	-2.1266	-1.6392	-1.8076	-521.017	-401.604	-442.862	-1.8393	-12.16697	-13.02992253	0.744688	7.092588109
-60	0	-2.0578	-1.604	-1.7966	-504.161	-392.98	-440.167	-1.7971	-11.88782	-12.80214266	0.835992	7.691287662
-60	0.5	-1.9851	-1.566	-1.7837	-486.35	-383.67	-437.007	-1.7523	-11.59146	-12.55804027	0.934269	8.33868554
-60	1	-1.9125	-1.5259	-1.7703	-468.563	-373.846	-433.724	-1.7075	-11.29511	-12.32298719	1.056526	9.100172178
-60	1.5	-1.8391	-1.4954	-1.7561	-450.58	-366.373	-430.245	-1.6631	-11.00141	-12.025797	1.049376	9.311450326
-60	2	-1.7665	-1.4648	-1.7417	-432.793	-358.876	-426.717	-1.6192	-10.71101	-11.73205259	1.042532	9.532665729
-60	2.5	-1.6932	-1.4271	-1.7269	-414.834	-349.64	-423.091	-1.5752	-10.41995	-11.47149812	1.105758	10.09170217
-60	3	-1.6207	-1.3887	-1.7117	-397.072	-340.232	-419.367	-1.5306	-10.12492	-11.21647576	1.191496	10.78089375
-60	3.5	-1.5457	-1.3494	-1.6935	-378.697	-330.603	-414.908	-1.4854	-9.825921	-10.93506819	1.230207	11.28797177
-60	4	-1.4706	-1.3112	-1.676	-360.297	-321.244	-410.62	-1.4411	-9.532877	-10.65137272	1.251034	11.73304012
-60	4.5	-1.3958	-1.273	-1.654	-341.971	-311.885	-405.23	-1.3959	-9.233879	-10.34151369	1.226856	11.99534071
-60	5	-1.3199	-1.2337	-1.6287	-323.376	-302.257	-399.032	-1.35	-8.93025	-10.01174567	1.169633	12.11047479
-60	5.5	-1.245	-1.1956	-1.6079	-305.025	-292.922	-393.936	-1.3045	-8.629268	-9.708207497	1.164112	12.50326284
-60	6	-1.1673	-1.1554	-1.5812	-285.989	-283.073	-387.394	-1.2575	-8.318363	-9.365515598	1.09653	12.58845233
-60	6.5	-1.0902	-1.1163	-1.5578	-267.099	-273.494	-381.661	-1.211	-8.010765	-9.040154954	1.059644	12.85008303
-60	7	-1.0137	-1.0767	-1.5327	-248.357	-263.792	-375.512	-1.164	-7.69986	-8.710184195	1.020755	13.12133201
-60	7.5	-0.9339	-1.0361	-1.5041	-228.806	-253.845	-368.505	-1.1152	-7.377048	-8.347177945	0.941152	13.15065247
-60	8	-0.8534	-0.9955	-1.4756	-209.083	-243.898	-361.522	-1.0663	-7.053575	-7.98117867	0.860449	13.1508382
-60	8.5	-0.7758	-0.9549	-1.4468	-190.071	-233.951	-354.466	-1.0172	-6.728778	-7.628282823	0.809109	13.36802645
-60	9	-0.6888	-0.9106	-1.411	-168.756	-223.097	-345.695	-0.9623	-6.365615	-7.204281494	0.703362	13.17495733
-60	9.5	-0.6033	-0.8667	-1.3678	-147.809	-212.342	-335.111	-0.9053	-5.98856	-6.740233495	0.565014	12.55183312
-60	10	-0.523	-0.8271	-1.3392	-128.135	-202.64	-328.104	-0.8561	-5.663102	-6.369119683	0.498462	12.46698797
											296.8883	7.317886888

Appendix E

Code

[style=CStyle] /* UAV Smart Wing Control Program - Testing * -Bhagyesh Govilkar * * Function daq is data acquisition only. PID control occurs in the "control" function. Use estimateLift function to estimate lift and print data to file and to console in printdata. * All functions should be called from within the while loop in the main function to avoid recursion. * * TEST SEQUENCE: * Gust response with FP model guesses.... * Gust response with second guesses.... * Gust response with no control.... * */

include <wiringPi.h> include <wiringPiI2C.h> include <stdio.h> include <stdint.h> include <errno.h> include <string.h> include <math.h> include <time.h>

uint8_t data[4]; //4bytewordu int8_t data2[4]; //4bytewordu int8_t data3[4]; //4bytewordu int8_t data4[4]; //4byteword

unsigned int pres; // raw pressure double p_o ut; //pressureinkPaunsignedintpres2; //rawpressuredoublep_o ut2; //pressureinkPaunsignedintpres3; //rawpressuredoublep_o ut3; / 1.225; //densityinkgm$^-$3doubleairspeed; doubleaas; doubleap1; doubleap2; doubleap3; inti = 0; doubleL; doubleKp = 0.14324; //setproportionalgaindoubleKi = 2.0572; //setintegralgaindoubleKd = −0.00047687; //setderivativegaindoublee; doubleel; doubleint_e; doubleP; doubleI; doubleD; doubleoutput; doubledt = 0.01; doubledt1; doubledt2; dou 0.021042611; doublew2 = −0.022570784; doublew3 = 0.025133973; intfd; intfd2; intangle; intpos = 0; intcounter = 0; doublestart_t ime; structtimespecgettime_n ow; doubleinit_t ime; uint8_t c 0x01; //addressforpitotprobereadinguint8_t ch$_2$ = 0x02; //addressfor1stpressuresensoruint8_t ch$_3$ = 0x04; //addressfor2ndpressuresensoruint8_t ch$_4$ = 0x08; //addressfor3rdpressurese fp = NULL;

void main() //acquire pressure reading from pitot probe and calculate airspeed clock_g ettime(CLOCK_R EALTIME, gettime_n ow); init_t ime = gettime_n ow.tv_s ec + (gettime_n ow.tv_n sec)/1000000000; fp = fopen("data.csv", "a"); fprintf(fp, " − − − − − − − − − − − GUSTRESPONSEACTUAL2 − − − − − − − − − − − "); fflush(fp); if(wiringPiSetup() == −1)//setuptouseWiringpinnumbersfprintf(stdout, "oops : return1; softServoSetup(0, 1, 2, 3, 4, 5, 6, 7); intfd = wiringPiI2CSetup(0x28); //0x wiringPiI2CSetup(0x77); //0x77I2Cdeviceaddresswhile(1)clock_g ettime(CLOCK_R EALTIME, gettime_n ow); start_t ime = gettime_n ow.tv_n sec; counter+ = 1; daq(fd, fd2); estimateLift();

void daq(int fd, int fd2) //acquire data and average 50 consecutive readings from each sensor while(i<40) wiringPiI2CWrite (fd2, ch$_1$); //selectchannelread(fd, data, 4); //reque (((int)(data[0]0x3f)) << 8)|data[1]; //acquiringpressuredatainnumberof"counts"p_o ut = 1.058 * pres − 8620; //conversionandcalibrationtogivepressureinkPaairspeed = sqrt(fabs(2 * p_o ut/rho)); aas+ = airspeed − 2.5; i+ = 1; aas = aas/40; i = 0;

while(i<40) wiringPiI2CWrite (fd2, ch$_2$); //selectchannelread(fd, data2, 4); //request4bytedatafromdevicepres2 = (((int)(data2[0]0x3f)) << 8)|data2[1]; //acquiringpressured 1.098 * pres2 − 8914; //conversionandcalibrationtogivepressureinPaap1+ = p_o ut2; i+ = 1; ap1 = ap1/40; i = 0;

while(i<40) wiringPiI2CWrite (fd2, ch$_3$); //selectchannelread(fd, data3, 4); //request4bytedatafromdevicepres3 = (((int)(data3[0]0x3f)) << 8)|data3[1]; //acquiringpressured 0.9036 * pres3 − 7371; //conversionandcalibrationtogivepressureinkPaap2+ = p_o ut3; i+ = 1; ap2 = ap2/40; i = 0;

while(i<40) wiringPiI2CWrite (fd2, ch$_4$); //selectchannelread(fd, data4, 4); //request4bytedatafromdevicepres4 = (((int)(data4[0]0x3f)) << 8)|data4[1]; //acquiringpressured 1.146 * pres4 − 9357; //conversionandcalibrationtogivepressureinkPaap3+ = p_o ut4; i+ = 1; ap3 = ap3/40; i = 0;

void estimateLift() //to estimate lift using acquired pressure data L=(w1*ap1+w2*ap2+w3*ap3);

void control() //run PID iteration and actuate e=L-3.2; P = Kp*e; if(output<-1) output=-1; else if(output>1) output=1; else int_e+ = e; I = Ki * int_e * dt; D = Kd * (e − el)/dt; output = (P + I + D); el = e; angle = −550 * output + 550; softServoWrite(0, angle); / * if(counter >= 200)//uncommentforstepresponsesoftServoWrite(0, 0 /

void printdata() //print data to console and file, set all average values to 0 //printf("clock_g ettime(CLOCK_R EALTIME, gettime_n ow); printf("clock_g ettime(CLOCK_R EALTIME 0; ap1 = 0; ap2 = 0; ap3 = 0; i = 0;