CONTROL SYSTEM DESIGN USING SPREADSHEETS

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The design of the mechanical control system for a light aircraft or glider can be very complicated. Specific elements such as the flap- aileron mixer are especially problematic. There exist a number of CAD programs that can simplify this matter. These programs are however not free and it is often not justified to buy a program for a single problem.

Today almost everybody has access to a spreadsheet that comes as a standard desktop tool. This paper shows that it is possible to model complex mechanical control systems quickly and easily on a spreadsheet. The whole system is graphically visible and control movements can be interactively changed with the mouse.

The powerful optimisation routines build into the spreadsheet allows the system to be optimised and refined in a fraction of the time possible with other methods. The paper shows how a flap-aileron mixer for a new 18m-class glider was developed using this method.

INTRODUCTION

The mechanical control system of a light aircraft or a glider can be described as a kinematic chain. This is defined as assemblage of links and joints interconnected in a way to provide a controlled output motion in response to a supplied input motion. Due to the interaction of the various elements in the kinematic chain and the difficulty in visualizing the movements it can be very difficult to design and optimise such a system. Some modern CAD systems offer the user the option of simulating the movement and to check for geometric anomalies. These software packages are normally very expensive and beyond the reach of a small or new company.

This problem can however be easily circumvented by the use of a spreadsheet. Almost all standard desktop word processing bundles include a spreadsheet program. It is possible to use a spreadsheet to model the kinematics of a complete control system for a small aircraft. The results are interactively available via the mouse in a graphical format. This allows one the freedom to investigate the influence of changes on the system and to optimise the system quickly and easily.

Most control systems are designed so that sections of the system are two-dimensional or plane systems with fixed angles, often 90° , between adjoining sub-systems. The models developed in this paper will therefore be two-dimensional models.

CONTROL SYSTEM ELEMENTS

A mechanical control system can be broken down into three basic elements. These are link arm and slider elements. A link element is considered as a single rigid rod with pinned joints at each end. The basic parameter is the length of the link while the coordinates of the end points define the position. The rotational position is defined as the angle between the link and the vertical.

An arm is considered as a rigid rod with pinned joints at the ends and a single rotational point about which it can pivot. The basic parameters for the arm element are the two arm lengths and the angle between arms. The coordinates of the ends and the pivot point define the position of the arm. The rotational position of the arm is defined as the angle between arm two and the vertical.

A slider element is any element in which the one end of a link can slide along a prescribed path. Cams are also considered as slider elements. Slider elements will not be modelled in detail in this paper. Figure 1 shows the definition of the three elements with the basic parameters associated with each element.

CONTROL SYSTEM MODELLING

When combining the basic elements to form a kinematic chain or control system, the problem is finding the position of each of the elements based on the input values and the geometrical constrains of the system. The geometrical constrains are the system parameters like link and arm lengths, and pivot positions.

The most basic system is a single arm with a specific pivot position and known position of one of the arm coordinates. This then defines the rotational angle of the arm as well as the position of the second arm. If the pivot position $(x_2,y_2)$and the position of the first arm (x_1,y_1) is known the rotational angle and the position of the output arm is simply:

$$\theta_2 + \theta_{ref} = a\tan\left(\frac{x_2 - x_1}{y_2 - y_1}\right)$$

$$x_3 = x_2 + r_2\cos(\theta_1 + \theta_2 + \theta_{ref})$$
$$y_3 = y_2 + r_2\sin(\theta_1 + \theta_2 + \theta_{ref})$$

$_{ref}$ is a reference angle from which the initial position of

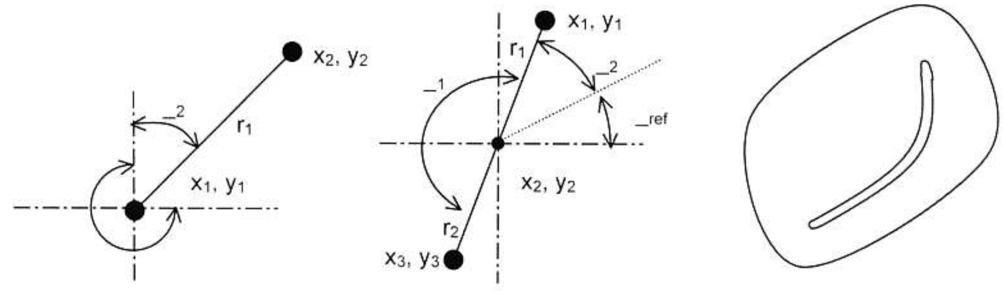


Figure 1:Link, arm and slider elements

arm1 is defined. $_1$ is the angle between the two arms, with $_2$ the rotational angle of the arm. This can be implemented into a spreadsheet as shown in Figure 2. In the upper left corner, the input data to the element is stored. The x and y offset is the position of the arm in Cartesian coordinates. The x and y coordinates for *in, mid, out* are the coordinates for the input, pivot and output arms. These coordinates are used to prepare the graphical coordinates, which are shown in lower cells. The graphical coordinates are the four coordinates required to draw two straight lines in a spreadsheet chart to form the arms of the belcrank.

The arm element as is shown in Figure 2 forms a standalone element for arms. If more than one arm element is used in simulation this element can be copied and pasted as many times as required. This model represents an arm with lengths of the individual arms respectively 50 and 75 mm. The reference angle is 0° with 60° between the two arms. The pivot point is situated at the coordinate (400,100).

Belcranck		superarm
θref	0.000	0.000
01	60.000	1.047
θ0	-88825	-1.550
r1	75.000	
r2	50.000	
	X	Y
OFFSET	400.000	100.000
in	401521	25.807
mid	400.000	100.000
out	443.805	75.893
Coordinates		
x	y	r
401.521	25.307	74.208
400.000	100000	50.000
400.000	100000	
443.805	75.393	

Figure 2: Arm element as implemented in spreadsheet

The next system to be considered is a link coupled to a single arm. The problem here is to find the position of the link-arm pinned connection, based on the physical constrains of the system.

Figure 3 shows a link coupled to an arm. Line AB represents the link with length r_1 while BC represents the arm with length r_2 and the pivot point C (x_2,y_2). The coordinates of A and C are known and the object is to find the coordinates of B.

This can be obtained by calculating the intercept of the circle with origin A and radius r1 and circle with origin C and radius r_2. This approach is however difficult to implement on a spreadsheet so that a direct geometrical solution was derived as follows:

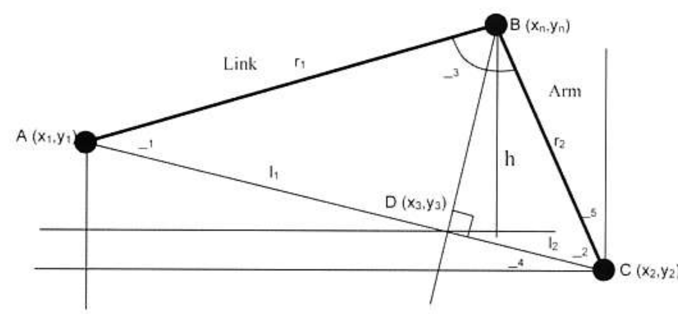


Figure 3: Link arm combination

Construction line AB can be drawn with BD perpendicular to AB. The coordinates of C can be calculated with the following procedure:

$$\theta_3 = a\cos\left(\frac{(l_1 + l_2)^2 - r_1 - r_2}{-2r_1r_2}\right)$$

$$\theta_1 = a\sin\left(\frac{r_2 \sin\theta_3}{l_1 + l_2}\right)$$

$$\theta_2 = a\sin\left(\frac{r_1 \sin\theta_3}{l_1 + l_2}\right)$$

$$\theta_4 = a\tan\left(\frac{y_1 - y_2}{x_2 - x_1}\right)$$

$$x_3 = x_1 + l_1 \cos\theta_4$$

$$y_3 = y_1 - l_1 \sin\theta_4$$

$$\theta_{10} = 90 - \theta_4$$

$$h = r_1 \cos\theta_1$$

$$x_n = x_3 + h\cos\theta_{10}$$

$$y_n = y_3 + h\sin\theta_{10}$$

These two simple systems allow the modelling of more complex systems. A more complex system can consist of a number of arms coupled together with links. The positions of each link-arm combination can be solved simultaneously to obtain the positions of all the links and arms in the system. Figure 4 shows how a link-arm combination is implemented on a spreadsheet.

The left-hand block is the arm element as before with the link element on the right. The input data of the link is on the left-hand side of the block and the calculated values on the right. The arrows show the coupling between the arm and link. The length of the link r_1 is fixed. r_2 is the length of the arm while x_2 and y_2 is the coordinates of the arm pivot point. This enables the calculation of the intercept point x_n and y_n, which can be used to calculate the graphical coordinate required to draw the arm and link element in the spreadsheet chart.

It is now possible to simulate a complete system of arms and links coupled together. This will be shown in the following section.

SIMULATING LARGER SYSTEMS

In this paragraph a typical aileron control system layout, as shown in figure 5, will be modelled. The system consist of an auto connector at the wing root, a link from the coupler to a belcrank a link to the aileron and then the aileron itself.

On the spreadsheet 3 arm elements and 2 link elements will be required. All the geometrical data is filled in for every element after which the couplings can be performed. Figure 6 shows the complete spreadsheet with couplings for this system.

Belcranck		superarm
θref	0.000	0.000
θ1	60.000	1.047
θ0	99.925	1.660
r1	75.000	
r2	50.000	
	X	Y
OFFSET	400.000	100.000
in	401.521	25.807
md	400.000	100.000
out	443.805	75.893
Coordinates		
x	y	r
401.521	25.307	74.208
400.000	100.000	50.000
400.000	100.000	
443.805	75.393	

Flap-Belcrank		Link	Calculated values		
r1	410.000		l	396.869	
r2	75.000		θ3	1.304	74.708
x1	3.925		θ1	0.183	10.603
y1	74.897		θ2	1.487	85.211
x2	400.000		l1	403.131	
y2	100.000		l2	6.261	
xn	401.521		θ4	-0.063	
yn	25.807		y3	100.396	
Invert	-1.000		x3	406.248	
Coordinates			θ10	1.634	
x	y	r	h	74.738	
3.925	74.897	400.615	θ5	-1.550	-88.825
401.521	25.807	0.000		-501.956	0.000

Figure 4: Arm and link implementation in a spreadsheet

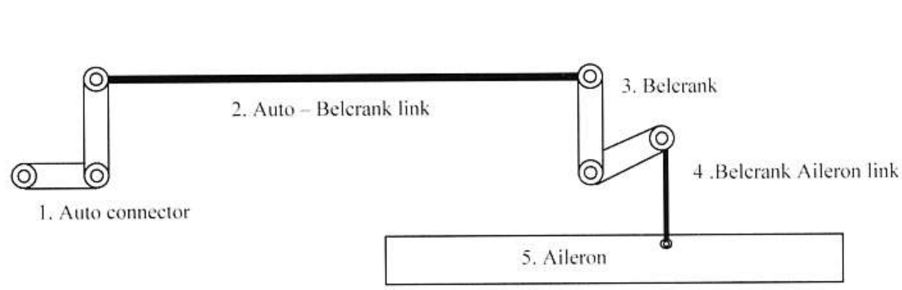
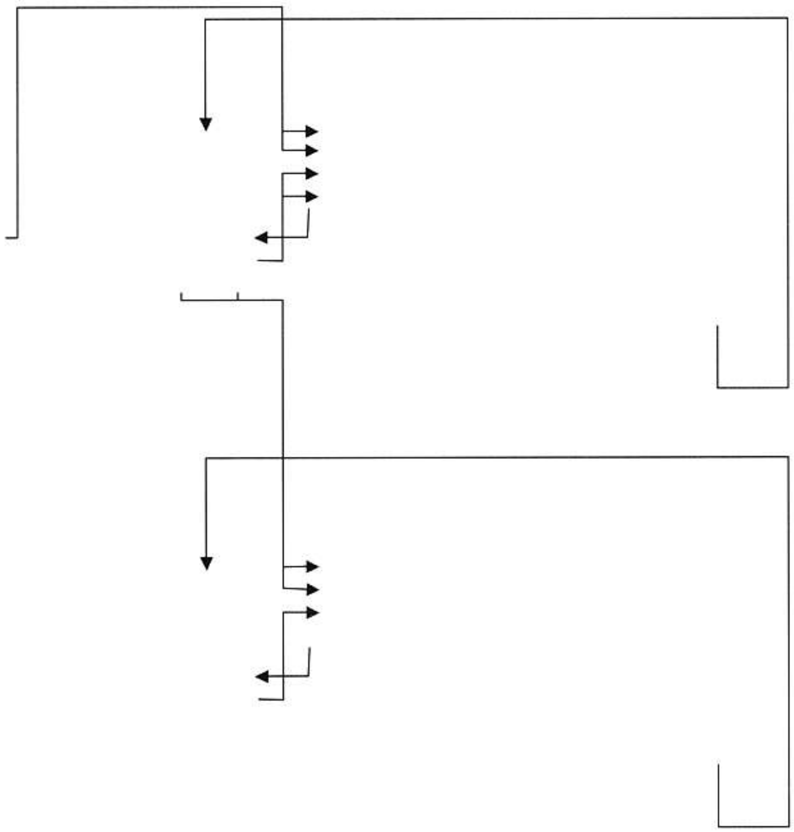


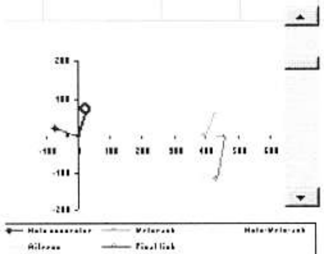
Figure 5: Aileron control system in aircraft wing



Auto connector		superarm
θref	180.000	3.142
θ1	270.000	4.712
θ0	-17.000	-0.297
r1	75.000	
r2	75.000	
	X	Y
OFFSET	0.000	0.000
in	-71.723	21.928
mid	0.000	0.000
out	21.928	71.723
Coordinates		
x	y	r
-71.723	21.928	75.000
0.000	0.000	75.000
0.000	0.000	
21.928	71.723	

Belcrank		superarm
θref	0.000	0.000
θ1	290.000	5.061
θ0	64.320	1.131
r1	75.000	
r2	60.000	
	X	Y
OFFSET	400.000	0.000
in	431.910	67.873
mid	400.000	0.000
out	459.755	-5.417
Coordinates		
x	y	r
431.910	67.373	75.000
400.000	0.000	60.000
400.000	0.000	
459.755	-5.417	

Auto-Belcrank		Link	Calculated values		
r1	410.000		l	384.815	
r2	75.000		θ3	1.141	65.358
x1	21.928		θ1	0.178	10.204
y1	71.723		θ2	1.319	75.562
x2	400.000		l1	403.515	
y2	0.000		l2	18.700	
xn	431.910		θ4	0.187	
yn	67.873		y3	-3.485	
Invert	1.000		x3	418.373	
Coordinates			θ10	1.383	
x	y	r	h	72.631	
21.928	71.723	410.000	θ5	1.131	64.820
431.910	67.873	0.000		-398.459	0.000

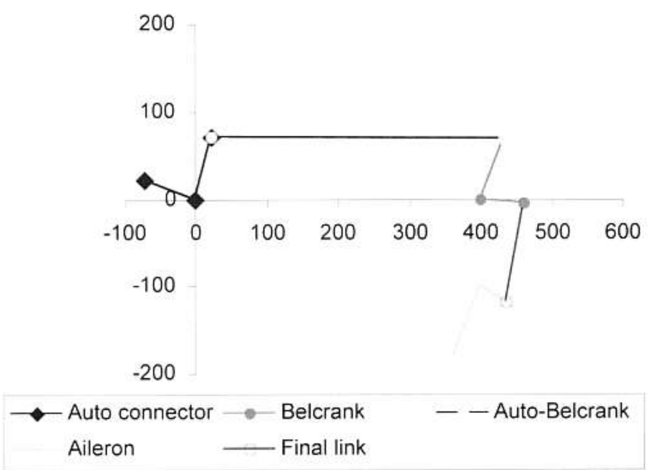


Aileron		superarm
θref	0.000	0.000
θ1	270.000	4.712
θ0	-26.567	-0.464
r1	40.000	
r2	86.000	
	X	Y
OFFSET	400.000	-100.000
in	435.777	-117.890
mid	400.000	-100.000
out	361.538	-176.920
Grafieke		
x	y	r
435.777	-117.890	40.000
400.000	-100.000	86.000
400.000	-100.000	
361.538	-176.920	

Belcrank - Aileron			Link	Calculated values	
r1	115.000		l	111.877	
r2	40.000		θ3	1.317	75.468
x1	459.755		θ1	0.353	20.249
y1	-5.417		θ2	1.471	84.283
x2	400.000		l1	107.893	-59.755
y2	-100.000		l2	3.985	
xn	435.777	yn-y2	θ4	2.134	122.284
yn	-117.890	-17.890	y3	-96.631	
Invert	1.000		x3	402.128	
Coordinates			θ10	-0.563	
x	y	r	h	39.801	
459.755	-5.417	115.000	θ5	-0.463675	-26.567
435.777	-117.890	0.000		-9.691	0.000

Figure 6: Spreadsheet model for aileron control system

The couplings must be performed by hand, but it is very simple and quick. The output result is the graphical representation in the left-hand corner. The input to the simulation is a mouse-controlled scrollbar. The values of the scrollbar can be set and is linked to the rotational angle of the auto connector. The simulation provides a real-time graphical simulation result, which proves to be very useful in the design of control systems. Figure 7 shows the graphical representation of the system in more detail. The parametric nature of the spreadsheet element models allows quick changes to the geometry and the ability to view the results immediately. This simplifies the optimisation of the system greatly.



THE DESIGN OF A FLAP AILERON-MIXER FOR A NEW 18M CLASS GLIDER.

This design tool becomes even more useful when a large and complex system such as a flap aileron mixer needs to be analysed. The requirement was to design a flap aileron mixer where the flaps and ailerons will moved together for most of the range of the flaps and of the ailerons in a flaperon mode. The exception is however in the landing mode. The flaps then goes to the 40° position while pushing the ailerons back to the -6° position. This is similar to the system used by Alexander Schleicher on their flapped gliders.

The system was designed with the mixer situated in the fuselage. Auto connectors join the controls from the mixer to the system in the wings. The resultant spreadsheet model is shown in Figure 7. The flap input is connected to two 90° arms. On each of these arms, belcranks are mounted which is connected to the aileron input. These belcrankcs are connected to the auto connectors for the flap and aileron.

The flap movement causes the 90° arms to move the belcranks on them up and down for flap control. The aileron input causes the belcranks to rotate for aileron control. A reverse mechanism is incorporated into the flap input which causes the aileron to move in the opposite direction after a certain forword flap motion. This mechanism is simply an arm, which slides in a slot. After the end of movement is reached, the arm rotates to create the reverse motion. This was also easily modelled in the spreadsheet by limiting the y motion of a normal arm. Figure 8 shows the mixer in the landing configuration with ailerons in the negative position. Figure 9 shows the mixer with neutral flaps and aileron fully deflected.

The spreadsheet model was then used to create charts for the input and output movements of the mixer system. A simple Visual Basic routine was written in Excel to use the mixer model as transfer function to create the data. This function calculates all the data by simply clicking on the calc button. It is thus very quick and easy to evaluate the influence of specific parameters on the system response.

Figure 10 shows the deflection of the flap and aileron with input only from the aileron. This is for flap at the 0° position.

It can be seen that the flap and aileron follows each other very closely with the aileron deflecting slightly more in the high positive range. The differential up and down movement of the ailerons is also visible. The differential is nearly zero in the middle range and increase toward the larger deflections.

Figure 10 shows the deflections for the flap and aileron with input from the flap with ailerons in the zero position. The movement is very linear. The ailerons follows the flaps to the +25° position and then rapidly moves to the -6° position as the flaps goes into the landing mode.

The design therefore fulfils the requirements set out in the beginning. The design of the mixer was very much simplified by the use of the spreadsheet models. It is very easy to spot problems in the graphical display and the detailed graphs enable a very quick and easy evaluation of the system performance .

CONCLUSION

In this paper, it was shown that a spreadsheet programme like EXCEL can be used to model control systems consisting of simple link arm and slider elements. By using simple component models coupled together, it is possible to model large and complex systems. The parametric nature of the element models allows quick and easy changes to the design. It was shown how this approach can be used to model a simple aileron system in a wing of an aircraft. Lastly the design of a complex aileron flap mixer model was discussed and the design results shown.

[i] Norton, R.L.,1999, Design of Machinery 2nd ed., Boston,: McGraw-Hill, 765p.

[ii] Heide, M, 1993, ASH26 Handbook, Alexander Schleicher

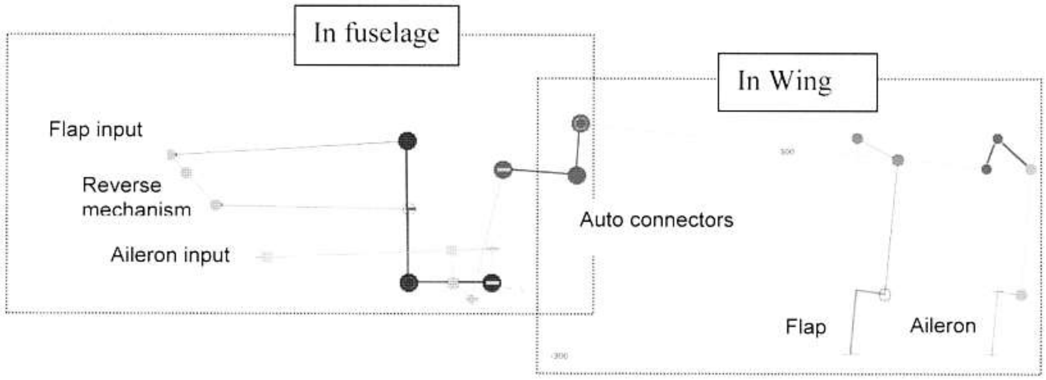


Figure 7:Excel representation of the Aileron flap mixer.

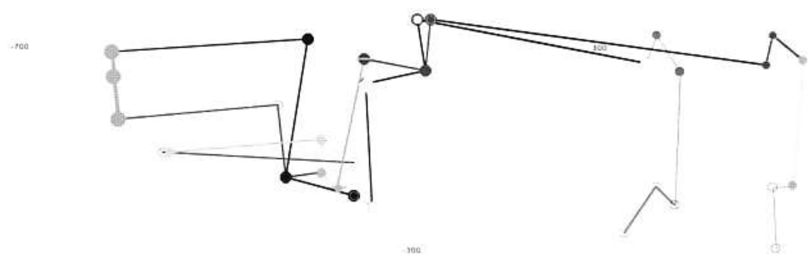


Figure 8: Mixer in full flap deflection mode

Figure 9: Mixer in full aileron deflection mode

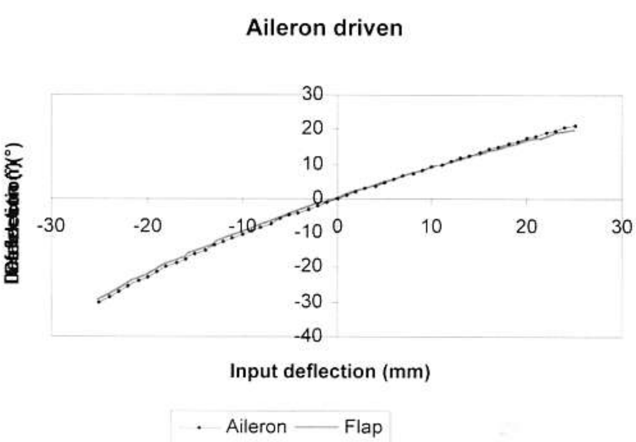


Figure 10: Aileron and flap deflection against input aileron deflection

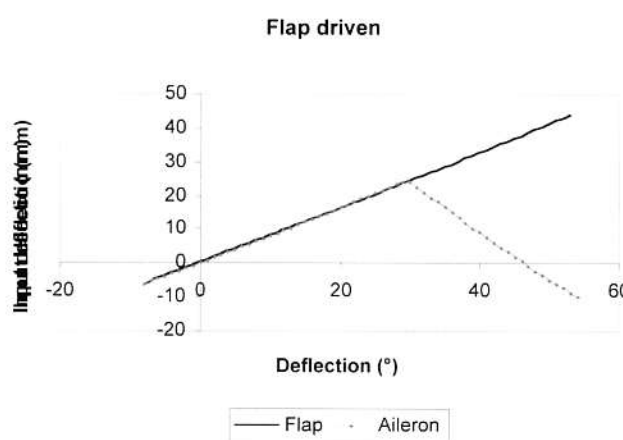


Figure 11 Aileron and flap deflection against flap input deflection