Design of Dynamics

Another use of feedback is to change the dynamics of a system. Through feedback, we can alter the behavior of a system to meet the needs of an application: systems that are unstable can be stabilized, systems that are sluggish can be made responsive and systems that have drifting operating points can be held constant. Control theory provides a rich collection of techniques to analyze the stability and dynamic response of complex systems and to place bounds on the behavior of such systems by analyzing the gains of linear and nonlinear operators that describe their components. An example of the use of control in the design of dynamics comes from the area of flight control. The following quote, from a lecture presented by Wilbur Wright to the Western Society of Engineers in 1901 [McF53], illustrates the role1.4. FEEDBACK PROPERTIES 19 of control in the development of the airplane: Men already know how to construct wings or airplanes, which when driven through the air at sufficient speed, will not only sustain the weight of the wings themselves, but also that of the engine, and of the engineer as well. Men also know how to build engines and screws of sufficient lightness and power to drive these planes at sustaining speed ... Inability to balance and steer still confronts students of the flying problem ... When this one feature has been worked out, the age of flying will have arrived, for all other difficulties are of minor importance. The Wright brothers thus realized that control was a key issue to enable flight. They resolved the compromise between stability and maneuverability by building an airplane, the Wright Flyer, that was unstable but maneuverable. The Flyer had a rudder in the front of the airplane, which made the plane very maneuverable. A disadvantage was the necessity for the pilot to keep adjusting the rudder to fly the plane: if the pilot let go of the stick, the plane would crash. Other early aviators tried to build stable airplanes. These would have been easier to fly, but because of their poor maneuverability they could not be brought up into the air. By using their insight and skillful experiments the Wright brothers made the first successful flight at Kitty Hawk in 1903. Since it was quite tiresome to fly an unstable aircraft, there was strong motivation to find a mechanism that would stabilize an aircraft. Such a device, invented by Sperry, was based on the concept of feedback. Sperry used a gyro-stabilized pendulum to provide an indication of the vertical. He then arranged a feedback mechanism that would pull the stick to make the plane go up if it was pointing down, and vice versa. The Sperry autopilot was the first use of feedback in aeronautical engineering, and Sperry won a prize in a competition for the safest airplane in Paris in 1914. Figure 1.14 shows the Curtiss seaplane and the Sperry autopilot. The autopilot is a good example of how feedback can be used to stabilize an unstable system and hence “design the dynamics” of the aircraft. One of the other advantages of designing the dynamics of a device is that it allows for increased modularity in the overall system design. By using feedback to create a system whose response matches a desired profile, we can hide the complexity and variability that may be present inside a subsystem. This allows us to create more complex systems by not having to simultaneously tune the responses of a large number of interacting components. This was one of the advantages of Black’s use of negative feedback in vacuum tube amplifiers: the resulting device had a well-defined linear input/output response that did not depend on the individual characteristics of the vacuum tubes being used.

WRIGHT BROTHERS GET A LIFT

by DR. RICHARD STIMSON
in INVENTING THE AIRPLANE

A hundred years ago (1901) the Wright Brothers were disappointed with the performance of their glider at Kitty Hawk. This glider had bigger wings containing more than double the area than the one they had flown a year before. They were expecting much better results. Instead they found a significant lack in lifting power.

Wilbur and Orville suspected that the aeronautical data that they had used in their calculations for lift were erroneous. The famous glider pioneer, Otto Lilienthal, considered as the most important aeronautical experimenter of the nineteenth century, had developed the data. The brothers decided to find out for themselves the validity of the data by building a wind tunnel and generating their own data.

Why Airplanes Fly
Gliders and airplanes need to produce an upward force called lift that overcomes weight created by gravity in order to fly.

Lift is created by the flow of air over a wing. In general there are two concepts of physics involved. One is Bernoulli's Theorem developed by Daniel Bernoulli, an eighteenth century scientist. He discovered that as the velocity of a fluid (such as air) increases, its pressure decreases.

In the case of an airplane, the wing is shaped to force the air flowing over the upper surface of the wing to flow faster than the air flowing over the lower surface. The faster air on the top surface creates a pressure differential resulting in an upward force on the wing.

Another contribution to lift comes from the effect of Newton's third law. Isaac Newton has been regarded for over 300 years as the founding exemplar of modern physical science. Newton's Third Law states that for every action there is an equal and opposite reaction.
As air passes over a wing, it is bent down. The bending of the air creates a downward force whose opposite equal force creates lift.

Determinants of Lift
There are a number of variables associated with creating and measuring lift. These include the size of the wing, the velocity of the air flowing over the wing, the density of the surrounding air, the shape of the wing and the angle of attack.

Area: All other things being equal, the larger the area of the wing, the more lift that will be created.

Wing Velocity: The higher the velocity the greater the lift. When an airplane is taking off, it normally heads into the wind because that increases the relative wind speed over the wings and helps the airplane reach flying speed.

Air Density: Air density refers to the amount of air contained in a given volume. Air density varies with the air's temperature and pressure.

Decrease temperature and density increases. Increase pressure and density increases. Air is denser at sea level than it is at higher elevations.

The denser the air, the greater the lift. The air pressure at Kitty Hawk, being at sea level, is denser than the air at Dayton, Ohio. The temperature at Kitty Hawk on the day of the first flight was a cold 34 degrees. The Kitty Hawk Flyer may not have gotten off the ground in Dayton's less dense air.

Coefficient of Lift: The coefficient is a multiplying factor that takes into consideration the various angles a wing assumes with regard to the flow of air. The value of the coefficient varies with the size of the wing and the "angle of attack."

The angle of attack is the angle of the wing with relation to the wind flow. Raising and lowering the nose of an airplane while flying varies the angle of attack. Within limits, a greater angle of attack results in greater lift.

Raising the nose to an extreme angle of attack can result in loss of efficient airflow over the wing and result in loss of lift. This is called a stall and is a potentially dangerous condition.

Lilienthal is one of a number of early experimenters that were killed when their gliders went into a stall condition. While gliding in 1896 at an elevation of 50 feet, a gust of wind caught his glider causing it to nose up sharply. He was not able to correct the problem by shifting his weight and crashed. That accident was fatal for Lilienthal who received a broken spin.

Lilienthal in the Pocket Book of Aeronautics published a table containing coefficients of lift in 1895. They later appeared in The Aeronautical Annual and other sources available to the Wrights.

Smeaton's Coefficient: Also involved in the calculation of lift at the time of the Wright Brothers was a constant number known as the "coefficient of air pressure." It is a multiplying factor used to calculate the numerical value of lift in air, as compared to other mediums, such as water or oil. John Smeaton, a mideighteenth century engineer, had determined the value of this coefficient was 0.005 in 1759, from his study of windmills. Engineers used the value of 0.005 for 150 years. The Wrights would subsequently find that this number was the major cause of their lift problem with their early gliders.

Modern aeronautical engineers no longer use Smeaton's coefficient. Many have never even heard of it.

Camber: A barn door can fly, but not very well. A wing with a cambered shape is more efficient; that is, one that has a degree of curvature of the upper surface.

The Wrights tested over 200 airfoils to find the optimum shape in a 6-foot pioneering wing tunnel they designed and built. Airfoil number 12 was found to be the most efficient and was the model for the wing used on their successful first flight in 1903.

The Wind Tunnel

The Wright Brothers did not invent the wind tunnel, but they were the first to use it for scientific aeronautical research directly related to the design and construction of an airplane. There were ten wind tunnels in the world at the time and the Wrights was the third in the U.S.

Their wind tunnel was not elegant; at a glance it looked like a coffin. But it was in fact an elegant scientific instrument that would set the standard for conducting aeronautical research up to the present time.

The tunnel was a simple wooden box six feet long and sixteen inches square. It had a glass window in the top for viewing the measuring instrument they had designed. A one horsepower engine they used in their shop drove a fan that generated a wind of thirty miles per hour. It turned out that the wind generated in the wind tunnel was almost the same as the wind the Wright Flyer faced at Kitty Hawk on the first successful flight (27-mph).

They fitted a honeycomb grid on the fan end of the tunnel, which produced a perfectly straight current of wind required for accurate measurements. This gave them their biggest problem and took them a month to solve.

Their engineering expertise was demonstrated in the instrument that they devised to measure lift. It consisted of an ingenious mechanical balance device in which the test wing foil was compared to flat plates placed perpendicular to the wind flow. The coefficient of lift could be read directly from the instrument.

The completed wind tunnel was capable of testing a wide range of shapes and curvatures to an accuracy of 2-3%. Lilienthal, in contrast, tested and published data on only one specific curvature.

Found a Significant Error

The wind tunnel tests conducted by the Wrights proved that Smeaton’s coefficient of air pressure was in error. The Wrights’ discovered that the correct average value for this coefficient was 0.0033 rather than Smeaton’s 0.005 they had used in designing the 1900 and 1901 gliders. This error was the primary cause of their poor performance. Using the Smeaton value of 0.005 had caused them to overestimate the force of lift in their design by 40%.

They also found an error in Lillenthal’s lift coefficients, but it was a minor error within the angles of attack they would be flying. There was close coincidental correlation between the Wrights’ and Lilienthal’s coefficients between five and eight degrees of attack.

The Wrights had for the first time in history established a scientific basis for designing an airplane that would perform in accordance with prior calculations. Previous experimenters had relied on guesswork using trial and error. The Wrights relied on facts and figures. They now knew how to design a wing in which they could have confidence that it would fly.

On December 7, 1901, their sister Katharine wrote to their father:
"…The boys have finished their tables of the action of the wind on various surfaces, or rather they have finished their experiments. As soon as the results are put in tables, they will begin work for next season's bicycles …"

New Design
In 1902, the year that "animal crackers" were introduced to America's children, they returned to Kitty Hawk with a new glider. Its design incorporated all their wind tunnel data. The wingspan was now 32 feet, ten feet longer than the 1901 glider with a longer and narrower shape with a camber of 1 to 20.

The wing area of 305 square feet was only slightly bigger than the 290 square feet of their previous year's glider, yet it generated much greater lift.

Their experiments enabled them to select a new wing shape with an efficient lift-to-drag ratio. Drag refers to the resistance that the wing generates as it flows through the air. The most efficient wings are those that generate the least drag for the most lift.

Their data demonstrated that longer, narrower wings in general produce more lift than the same area contained in short, wide ones.

Their data also showed that a parabolic wing camber with the high point toward the front was more efficient than the perfect arcs that Lilienthal and others had used.
The camber they used on the 1902 glider was a relatively flat 1 in 24 to 1 in 30 depending upon how the wing was rigged. This specific wing configuration was never actually tested in their wind tunnel. They apparently extrapolated this configuration from their other data.
All of the above were new and original conclusions resulting from their wind tunnel experiments. The Wrights' were now far ahead of anyone else in the aeronautical field.
World Record Flights

They flew their new glider somewhere between 700 and 1,000 times during their five weeks of experimenting at Kitty Hawk. On October 23, Wilbur sailed 622 1/2 feet in 26 seconds setting new American records.

"We now hold all the records! The largest machine we handled in any kind of weather, made the longest glide, the longest time in the air, the smallest angle of descent and the highest!!!"
They were now convinced that the data they had found from their wind tunnel tests would enable them to calculate in advance the performance of their first powered airplane. They had mastered two of the three conditions of flight. They had designed wings capable of sustaining flight and developed a three-axis control system that allowed maintaining balance and executing turns. The next step was to develop an engine and propeller.

Calculation of lift for the 1903 Kitty Hawk Flyer
The formula used to calculate lift is as follows:
$L = kxV^2xSxCL$ where

L = Lift (pounds)
k = Smeaton's coefficient
V = Relative Velocity of air over wing (mph)
S = Wing area (square feet)
CL = Coefficient of lift
$k = 0.0033$ (from Wrights' wind tunnel experiments)
$V = 33.8$ (wind of 27 mph on December 17, 1903 plus ground speed of Flyer of 6.8 mph)
$S = 512$ (wing area of 1903 Flyer)
$CL = 0.515$ (from Wrights' table of lift coefficients assuming airfoil #12 and an angle of attack of 5 degrees)

Substituting the approximate values for the 1903 Wright Flyer on the first flight:
$L = (0.0033) \times (33.8)^2 \times (512) \times (0.515) = 994$ pounds

The weight of the Flyer, including engine was 605 pounds. Orville weighed approximately 145 pounds. Therefore, the total weight of machine plus pilot is 750 pounds
Since lift (994 pounds) is greater than the weight of the machine (750 pounds), the lift was sufficient to support flight.