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The Outrigger: A Prehistoric Feedback Mechanism

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***Abstract*— "How does that work?" asked DJ, my 3 year old son. We were standing on the beach at Waikiki, looking at an outrigger canoe. He was pointing to the outrigger. Like any dutiful father, I started trying to explain the use of the outrigger. Halfway through my explanation, I realized that I was describing a feedback mechanism. A cursory knowledge of Polynesian history indicated that this was an ancient mechanism, quite possibly the first feedback mechanism created by humanity, predating the float valve by at least a millennium. This paper is my attempt to chronicle the history of this remarkable bit of Stone Age control engineering.**

I. Introduction

Fig. 1. The outrigger canoe on the beach.

There are two types of floating watercraft: those that owe their buoyancy to the material from which they are made, and those that owe their buoyancy to the amount of water that they displace. While the reed boats of Ancient Egypt and the balsa rafts of Peru are in the former class [1], the dugout canoe so prevalent in Polynesia belongs to the latter class [2]. The dugout canoe suffers from a tendency to capsize, as compared to plank-built vessels (vessels built of planks attached to some frame). Unlike the latter, there is limited ability to increase a dugout's resistance to capsizing (i.e. to increase its roll stability) by widening or changing the shape of the keel. Thus, the dugout canoe begs for a different solution to the roll stability problem.

At its most basic level, an outrigger consists of some sort of a float, attached via one or more booms to the gunwales (top edge) of a boat. While modern outriggers can be made from a variety of sturdy, buoyant materials, the outrigger float has traditionally been some piece of light wood, and the type of boat that it is most often associated with is a dugout canoe. However, outriggers are also found on plank-built boats, although the necessity is lessened for these vessels. Builders of plank boats have more ability to improve roll stability by changing the hull shape than makers of dugout canoes. The action of an outrigger is twofold. First, it adds buoyancy to the vessel, since outriggers are made of materials that float irrespective of their shapes. More importantly, the addition of a float at the end of the boom dramatically increases the roll stability of the small canoes to which outriggers are typically attached.

Until the publication of Otto Mayr's *The Origins of Feedback Control* [3], [4], the consensus among control engineers was that the original feedback mechanism built by human beings was Watt's flyball governor [5]. However, Mayr's work established convincing evidence that the water clock of Ktesibios who lived in Alexandria "in the first half of the third century B.C." was the first recorded feedback mechanism [3]. This predated the flyball governor by two millenia. A series of other devices based on the float valve, followed in the succeeding centuries, most of these appearing in the Middle East.

Otto Mayr's book also established a set of criteria to determine if a device was in fact a feedback mechanism [3].

> *The three criteria we have now obtained contain a sufficiently complete definition of the concept. Briefly repeated, they are:*
>
> *1) The purpose of a feedback control system is to carry out commands; the system maintains the controlled variable equal to the command signal in spite of external disturbances.*

2) *The system operates as a closed loop with negative feedback.*
3) *The system includes a sensing element and a comparator, at least one of which can be distinguished as a physically separate element.*

Using these criteria, this paper will argue that the outrigger on an outrigger canoe, the device that Heyerdahl referred to as "the most desirable of the Asiatic navigational inventions ([1],pp. 160–161)", is in fact a feedback mechanism. Furthermore, this device predates the float valve by at least a thousand years, making it the earliest feedback mechanism built by humans to be documented thus far.

The organization of this paper is as follows. Section II gives a cursory explanation of the dynamics of boat stability. Section III, discusses the use of an outrigger in providing roll stability for a dugout canoe. Section IV gives a qualitative description of the operation of an outrigger, specifically how it satisfies the Mayr criteria of a feedback mechanism. Section V delves into the origins of the outrigger and traces its progression around the world.

II. Basic Roll Stability

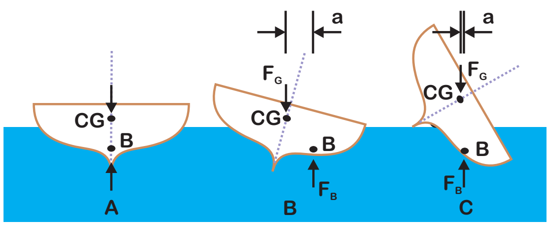

Fig. 2. Righting moment for a typical plank boat hull. (Reproduced from [6], p. 252.)

A key component of any watercraft is its roll stability. Put simply, a watercraft with poor roll stability will capsize easily. If the craft is made of heavier-than-water materials, then it relies on the displacement of water to achieve buoyancy. In such a situation, capsizing leads to the waterlogging of the vessel, which in turn leads to it sinking. Even for watercraft made of buoyant materials, capsizing puts people and cargo in the water.

Resistance to capsizing, or roll stability comes from having a righting moment that resists angular disturbances. Consider the typical plank-built boat cross section in Figure 2. The boat floats because it displaces water equivalent to its weight. As long as the boat can displace more water than its weight, it will be buoyant. For most boats with bilateral symmetry about the center line, this means that the center of gravity is above the center of buoyancy (Figure 2A). When the boat rotates around its center of gravity (Figure 2B), the center of buoyancy moves out from under the center of gravity, resulting in a moment opposing the rotation equal to $[F_G + F_B]\, a$.

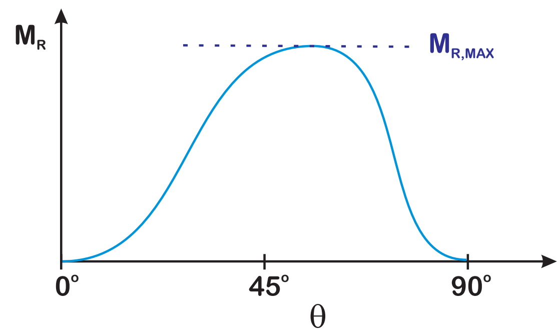

Fig. 3. A typical righting moment curve. The righting moment increases with increasing angle until some maximum value, $M_{R,MAX}$.

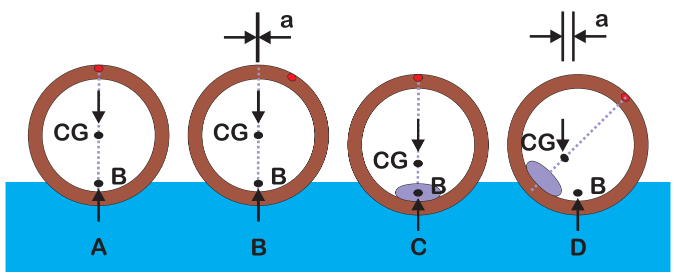

Fig. 4. A cylindrical hull has no roll stability, because the center of buoyancy is always under the center of gravity. Adding ballast at the bottom adds stability. An unballasted hull, made from a section of a cylinder, has generally poor roll stability.

As long as the center of buoyancy moves away from the center of gravity, the righting moment increases. At some point it reaches its maximum, and the moment arm and the righting moment start decreasing (Figure 2C). As the angle gets larger, the center of buoyancy gets closer to the center of gravity, lowering the effective righting moment. A typical shape of a righting moment curve is shown schematically in Figure 3.

The shape of the hull has a dramatic effect on the shape of the righting moment curve. In particular, a perfectly cylindrical hull with a circular cross section, as shown in Figure 4A, has no righting moment, since for an angular displacement, the center of buoyancy is still right under the center of gravity (Figure 4B). Adding ballast at the bottom of the hull lowers the center of gravity (Figure 4C), and allows for a righting moment (Figure 4D).

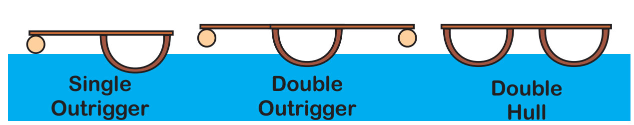

Fig. 5. Adding outrigging to stabilize a dugout hull.

One possibility for adding a righting moment to a cylindrical hull is to attach it to a second cylindrical hull. The farther apart the two hulls, the easier it is to generate a righting moment (at least for small angles). This can be done in one of several ways. Here we will concentrate on the three methods most closely associated with outrigger technology: a single outrigger, a double outrigger, and a double hull canoe, shown in Figure 5. We will see that all three are present in the sailing technology of the Austronesian peoples[1]. They all work on similar principles. The trade-offs in choosing one type of watercraft over another seem to have more to do with ease of manufacture, structural safety, and crew requirements for each type of craft.

Qualitatively, the operation of the outrigger is rather simple. When the canoe rotates so as to raise the boom from the water, its weight at the end of a moment arm provides torque to rotate the boom back to the surface. When the rotation of the canoe acts to push the boom into the water, the buoyancy of the boom acts to restore the boom to the surface of the water. *In other words, it senses and resists angular disturbances – truly a negative feedback mechanism.*

III. The Dugout Canoe

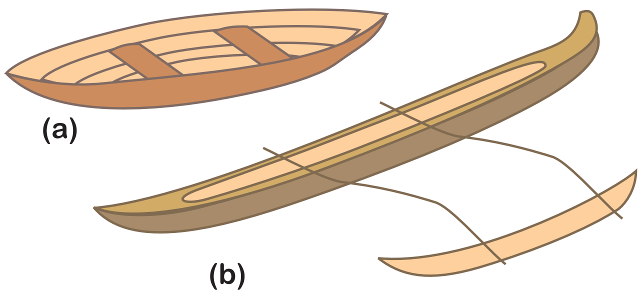

Fig. 6. Comparison of plank built (a) versus outrigger (b) canoe. Note the narrow hull of the outrigger as compared with the plank built hull.

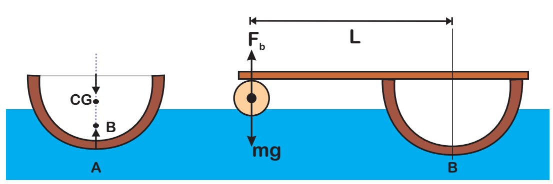

Fig. 7. An unballasted hull, made from a section of a cylinder, has generally poor roll stability. This is the case for the dugout canoe on the left. Adding an outrigger, on the right, creates a righting moment.

This section will present a simplified static analysis of a dugout canoe, showing the effect of adding an outrigger. The buoyant forces for various simple shapes of outrigger floats as a function of change in dept will be presented to show the development of righting moments.

A pictorial comparision of plank built and outrigger canoes can be seen in Figure 6. Unlike a plank-built boat, a dugout canoe is hollowed out of a single tree trunk. This limits the shape of the cross section to something that closely follows a portion of a cylinder. This has a very small inherent righting moment, as shown in Figure 7A. In other words, the roll stability is poor. However, the addition of an outrigger (Figure 7B) improves this situation considerably. From a feedback perspective, the outrigger adds a righting moment. In Figure 7B, the float has a nominal depth of d at which the buoyant force exactly cancels the force of gravity, i.e. $F_B(d) = mg$. For a disturbance that moves the depth away from the nominal by Δd,

$$\begin{aligned} M_R(\Delta d) &= [F_B(d+\Delta d) - mg]\, a && (1) \\ &= [F_B(d+\Delta d) - F_B(d)]\, a. && (2) \end{aligned}$$

Computing the righting moment for different configurations essentially consists of computing $F_B(d+\Delta d) - F_B(d)$. For a rotation of the main hull through an angle θ, the change in depth, Δd, is found by

$$\Delta d = L \sin\theta, \qquad (3)$$

while the moment arm of the buoyant force, a, is given by

$$a = L\cos\theta. \qquad (4)$$

This linearizes for small θ to

$$\Delta d = L\theta \text{ and } a = L. \qquad (5)$$

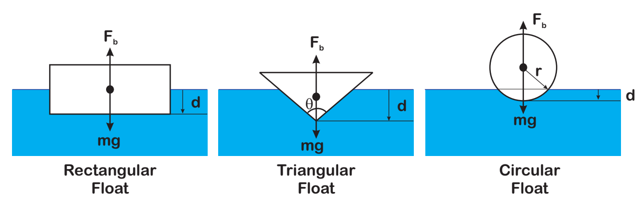

Fig. 8. Different float shapes yield different error equations.

It is rather straightforward, albeit tedious to compute the buoyant forces for different float cross sections. This is done in detail in the Appendix, while results are presented here. For all of these cross sections, the equations generated are in terms of the nominal depth of the float, d, the change in depth, Δd, and the float geometry. In these results, l is the length of the float, ρ is the density of the displaced water, and g is the acceleration due to gravity.

The first shape is the rectangular float, shown on the left side of Figure 8. This is the simplest to compute and is the one that gives a linear error equation, that is the resultant buoyant force as a result of the vertical displacement, Δd, is

$$F_{\Delta d} = \rho g \Delta d. \qquad (6)$$

[1]The term Austronesian is used by Doran [7] and others to describe the general set of people that moved out of Asia to Australia and into the Pacific. The name denotes a superset of the indigenous peoples of Australia, Indonesia, Malaysia, and Polynesia

A more likely pair of shapes for a float is one with a triangular cross section or a circular cross section, at the center and right of Figure 8, respectively.

For the cross section in the shape of an isosceles triangle, we would like to calculate the buoyancy as a function of the depth of the section, d. In this case the difference in forces is given by

$$\begin{aligned} & F_b(d+\Delta d) - F_b(d) \\ &= [V_{imm}(d+\Delta d) - V_{imm}(d)]\,\rho g \quad (7)\\ &= l\,[A_{d+\Delta d} - A_d]\,\rho g \quad (8)\\ &= l(2d\Delta d + (\Delta d)^2)\tan\frac{\theta}{2}\rho g, \quad (9)\end{aligned}$$

where θ is the angle of the triangle corner in the water. Now, the feedback term is dependent upon the nominal depth, d, and has a quadratic component.

If we repeat the same set of calculations for the circular cross sectional float, we must calculate the area of the submerged segment as a function of the radius, r, and the depth, d. This results in a difference in forces equal to

$$\begin{aligned} & F_b(r, d+\Delta d) - F_b(r, d) \\ &= l\Bigg[\Bigg(r^2\mathrm{Cos}^{-1}\frac{r-(d+\Delta d)}{r} - \\ & (r-(d+\Delta d))\sqrt{2r(d+\Delta d)-(d+\Delta d)^2}\Bigg) - \\ & \Bigg(r^2\mathrm{Cos}^{-1}\frac{r-d}{r} - (r-d)\sqrt{2rd-d^2}\Bigg)\Bigg]\rho g. \quad (10)\end{aligned}$$

For small Δd, Equations 9 and 10 both become linear in Δd, which matches physical intuition.

IV. The Outrigger as a Feedback Mechanism

The outrigger may have evolved from the custom of lashing two canoes together to provide greater roll stability. However, at first blush the double hulled canoe does not seem to qualify as a feedback mechanism since the second hull does more than just provide roll stability. First of all, unlike the outrigger, it is hard to distinguish which hull is the feedback mechanism and which hull is the main part of the boat. The second hull also increases the cargo capacity of the ship, and gives it more length in the water which decreases the wake and improves the speed [6],pp: 255–257. The outrigger itself provides no such extra capacity and thus its chief purpose is that of roll stability.

From the perspective of the Mayr criteria, the outrigger satisfies all three:

1) **The outrigger provides roll stability for the canoe.** That is, it keeps the canoe from capsizing. In this respect, the controlled variable is the angle between the bottom of the canoe and the surface of the water.
2) **The outrigger provides negative feedback.** From a nominal position on the water, the buoyancy resists rotations that would further submerge the outrigger and the weight resists rotations that would raise it out of the water.
3) **The outrigger itself is a separate element from the canoe.** It is the sensing element and the actuator for detecting and correcting rotations. Its only purpose is to provide roll stability.

The double outrigger makes the stabilization problem symmetric by putting a buoyant float on either side of the hull. The double hulled canoe also makes the problem symmetric, by adding a second hull in parallel to the first. Returning to a strict interpretation of the Otto Mayr criteria, the second hull might not be considered a feedback mechanism. However, the double hull canoe is an obvious member of the outrigger family, springing from the same culture and used in parallel with the outrigger canoes. Viewed in the context of other outriggers the double hull should be seen as a stabilization device. Thus, we consider all three forms to be instances of outrigger technology. As such, the age of one over another is not critical to understanding the age of outrigger technology, but is useful to study.

V. The Origins and History of Outrigger Canoes

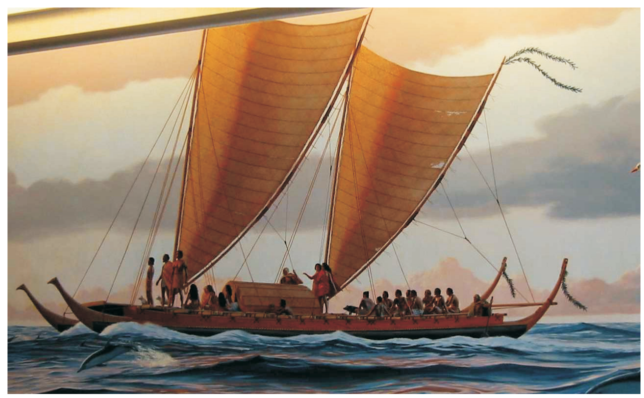

Fig. 9. Mural depicting ancient Polynesian voyaging canoe in the lobby of the Outrigger Waikiki Hotel.

Debates about the origins of outrigger technology are intimately connected to debates about who originally populated the South Seas, and when and how they did it. Central to both debates are questions about the seaworthiness of Polynesian canoes and the skills of Polynesian sailors. The absence of written records and scarcity of material remains of canoes fueled the debates[2].

The traditional view of Polynesian migration, island hopping across the Pacific in deliberate exploration, was codified by Peter Buck in his classic book, *Vikings of Sunrise*, later

[2]The ancient Polynesians had no written language. Furthermore, there were no traces of the ancient canoes as they were made of soft woods which would swiftly decompose in the warm waters of the South Pacific and Indian Oceans.

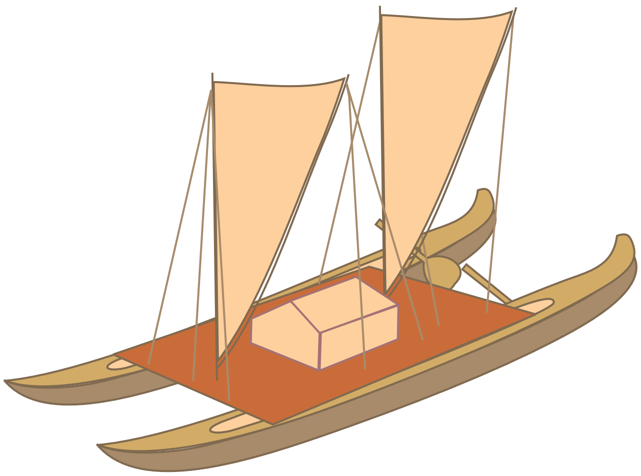

Fig. 10. Drawing of double hull Polynesian voyaging canoe.

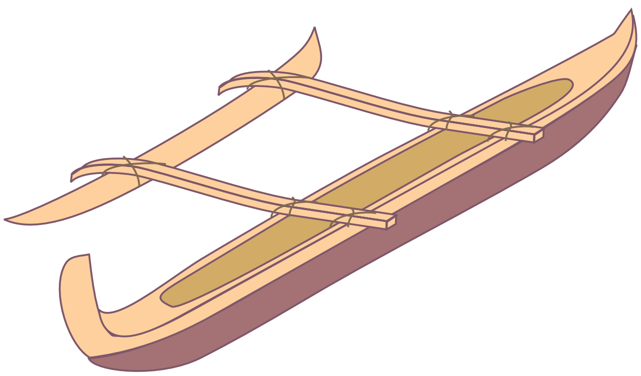

Fig. 11. Drawing of Hawaiian style single outrigger canoe.

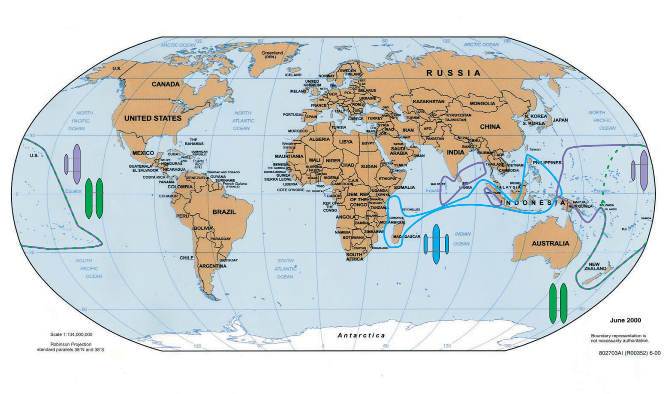

Fig. 12. The distribution of outrigger canoes across the world. Note the broader distribution of single outriggers to double outriggers. Data summarized from maps in Hornell [2] and Doran [7].

reissued as *Vikings of the Pacific* [8]. This theory came under attack from two sources: Thor Heyerdahl and Andrew Sharp. Heyerdahl claimed that the Polynesian canoes were too primitive to sail against the prevailing current and wind (which blows from East to West most of the year in the South Pacific). Based on this dismissal of the Polynesian craft, he proposed that Southern Polynesia was settled from South America while Hawaii was settled by Northwest Pacific Coast Native Americans, who had originally arrived at the Vancouver Archipelago in double canoes from Asia by way of the Humbolt current [9]. These Northwest Native Americans had followed the currents that lead Oregon pines that fall into the ocean to drift to Hawaii. Heyerdahl's theory was popularized by the experimental voyage of the Kon Tiki, a balsa wood raft which Heyerdahl and his crew sailed from South American to Polynesia, mainly by drifting on the prevailing currents. As the archaeological evidence supported migration from Asia, Heyerdahl's theories found little scientific support [10].

Andrew Sharp launched a different attack on the traditional theories. While he accepted Polynesian migration from Asia, he claimed that the Polynesian craft and sailing methods were too crude for anything but accidental migration. He dismissed theories and stories of intentional Polynesian exploration as "romantic nonsense" [11]. However, simulation studies showed that the probability of success with accidental migration was infinitesimally small [12].

To counter Sharp's and Heyerdahl's theories, a team led by Ben Finney at the University of California in Santa Barbara began a project to build a traditional Polynesian double hull canoe (shown in a mural in Figure 9 and in a simple drawing in Figure 10) and sail it between Hawaii and Tahiti by traditional Polynesian seafaring methods. The voyages of the Hokule`a [13], [10] proved that traditionally built and navigated Polynesian double hulled canoes were capable of voyaging long distances against the wind and finding remote islands. The boats proved extremely seaworthy, both in their ability to sail close to the wind, their stability, and their speed. Thus, the underlying premise of Sharp's and Heyerdahl's theories were invalidated. Finney also points out that such "Kamikaze migration" was not very logical. If one explores by sailing with the prevailing wind and current, then returning home is a real problem. However, if one sails against the wind and current to do exploration, then it is relatively easy to turn around and head home. The latter method seems much more likely to ensure the survival of the explorer.

Today, there is little debate that Polynesians are derived from the Austronesian peoples. The archaeological evidence suggests that the Austronesian peoples migrated from Southeast Asia somewhere between 40,000 and 30,000 years ago. Even with the lower ocean levels of the Pleistocene Era, this still meant crossing 100 miles of open ocean to get to Australia [14]. The Austronesians started moving out into the Pacific islands 3500 years ago. The lack of seaworthiness of dugout canoes, due to their stability problems, implies that one of the outrigger mechanisms must have been in use to make this possible. This pins the *minimum* age of outrigger technology at 3500 years. It is quite possibly associated with the migration to Australia, which would make it considerably older [14].

Another piece of evidence is in the migration from Asia to Polynesia. The Polynesians used both outrigger canoes (Figure 11) and double canoes, with the the latter being the primary vessel for long range exploration [13]. Finney points out [13] that the Polynesian culture itself is necessarily a seafaring culture: “Polynesian culture developed not in any Asian or American homeland, but in Polynesia itself. Seafarers ancestral to the Polynesians moved from eastern Melanesia to the uninhabited islands of Tonga and Samoa between 1500 and 100 B.C. They settled there, and over the centuries the basic Polynesian cultural pattern developed. Starting about the time of Christ, seafarers, full-fledged Polynesians now, moved from these western Polynesia centers to the east to settle first probably the Marquesas Islands and then the Society Islands (the most important of which is Tahiti).”

Stanley also places the origins of Polynesian migration at around 1500-1600 B.C: “Sometime after about 1600 B.C., broad-nosed, light-skinned Austronesian peoples entered the Pacific from Indonesia or the Philippines. . . . Three thousand five hundred years ago, the early Polynesians set out from Southeast Asia on a migratory trek that would lead them to make the ‘many islands’ of Polynesia their home. Great voyagers, they sailed their huge double-hulled canoes far and wide, steering with huge paddles and pandanus sails. To navigate they read the sun, stars, currents, swells, winds, clouds, and birds. Sailing purposefully, against the prevailing winds and currents, the Lapita peoples reached the Bismarck Archipelago by 1500 B.C., Tonga (via Fiji) by 1300 B.C., and Samoa by 1000 B.C. Around the time of Christ they pushed out from this primeval area, remembered as Havaiki, into the eastern half of the Pacific [15].”

Given the probable origins of the outrigger in Southeast Asia and the timing of the migrations into the Pacific, we can establish that the outrigger likely dates to at least 1500 B.C., 1200 years before the the water clock of Ktesibios.

Note that the use of the outrigger spanned most of the Pacific and Indian Oceans, from Easter Island and Hawaii in the east, to Madagascar in the west. Madagascar itself was first settled by Indonesians who crossed the Indian ocean in outrigger canoes approximately 2000 years ago [2]. To the east, the primary Polynesian exploration vessel was the double hulled canoe, ancestor to the modern catamaran [13]. The single outrigger canoe was a technology that they brought with them for their smaller craft. One of the main difficulties with making double hulled canoes was finding two matching logs of sufficient size. Among the most prized logs for canoe building were Oregon pines that fell into the ocean and drifted to Hawaii. They were so valued that logs would be kept for years until a matching one drifted ashore [2], [9]. The outrigger provided equivalent roll stability for a canoe made of only one large log.

Heyerdahl also points out differences between different types of outrigger canoes:

> *All through Indonesia, from Sumatra and the Philippines to the nearest tip of New Guinea, the Malays and Indonesians have since early times used the* double *outrigger to stabilize their craft, i.e., a buoyant boom fastened to crossbars on each side of the vessel. The Micronesians and the Melanesians used a* single *outrigger, that is on one side only, and for this reason the Micronesians built their canoes laterally asymmetrical. When the Polynesians adopted the single outrigger on their bilaterally* symmetrical *canoes they did not follow the Micronesian model but followed that of neighboring Fiji. In short, neither the Indonesian nor the Micronesian type of outrigger canoe reached the East Pacific [1] (pp. 160–161).*

Where each style of outrigger first appeared is a matter of some debate. Much of the source material on outrigger canoes comes from work by James Hornell, an official who worked in British India in the early part of the twentieth century. Hornell’s joint work with A. C. Haddon [16] remains the definitive source book for most research in this area. Many of the boats documented in the three volumes of *Canoes of Oceania* have passed from existence since the book was written in the 1940s. After his retirement, Hornell traveled the world to document the development of watercraft [2]. Although there has been more recent work on the subject, the source material often includes Hornell and Haddon’s work, since the disappearance of many of these watercraft in the past hundred years have made their books the main documentation on the vessels. One of the more recent studies was done by Edwin Doran. Doran looked at this same source evidence with more modern methods and came to opposite conclusions about the relative ages of different outriggers in his book, *Wangka: Austronesian Canoe Origins* [7]. Section V-A will discuss Hornell’s view while Section V-B will present Doran’s.

A. Hornell’s View

Outrigger canoes are closely associated with Indonesia. Hornell lists Indonesia as the center of dispersal of the outrigger ([2], pp. 263–269). However, Hornell goes on to point out that virtually all watercraft technology originated in rivers and marshes, rather than in the ocean ([2], pp. 264–265). Indonesia, lacking any significant lakes or rivers, is then a poor candidate for the origins of the outrigger canoe. Evidence is that the settlers of Indonesia migrated down from Southeast Asia, and it is this region, with its wide rivers that is the most likely cradle of the outrigger canoe. Hornell suggests that the Irrawaddy, Salween, and Mekong rivers, which “have been from time immemorial the only highways of migration available to the peoples pressing southwards

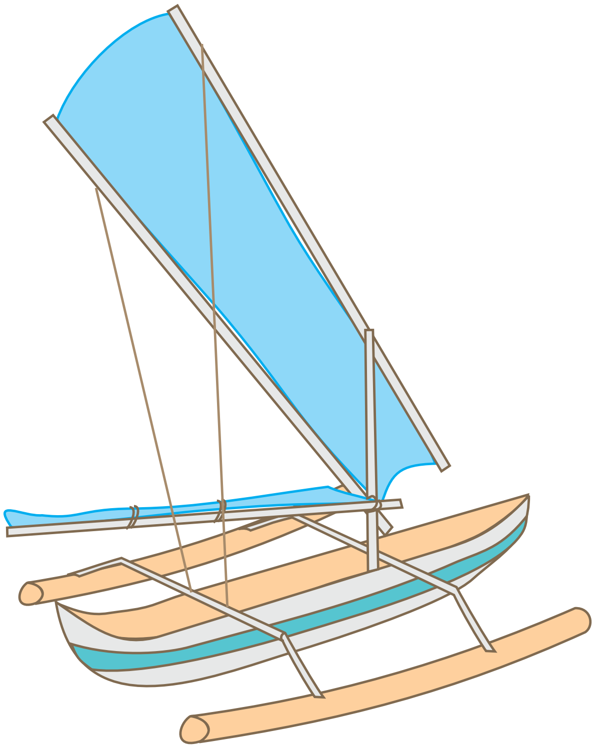

Fig. 13. Drawing of double outrigger canoe of style found in Indonesia.

from the cold and dreary mountain lands of the north to the fertile lower plains," as the likely locations. "Nowhere else can the development of the dugout canoe into sailing ships of large size be so clearly traceable, step by step, as on the great Burmese river. The dugout in general use by the river people, scattered in innumerable villages along its banks, is the most beautiful of its class. Hewn by men possessed of unconscious skill and inborn artistic feeling, the huge teak baulk is fashioned into a long and relatively narrow craft sheering upwards in a graceful curve toward each end, where it rises well above the water line like the horns of a gigantic crescent ([2], p. 265)." Hornell goes on to place the original outrigger craft at double outrigger with bamboo trunks for floats [2],(p. 266).

From these rivers, the migration to Indonesia was made necessarily by watercraft. Thus, for the outrigger to appear in Indonesia, it must have been used in the migration from Southeast Asia. Heyerdahl indicates that "outriggers [were] used on local proas[3] in Southeast Asia since the second millennium B.C. ([9], p. 64)."

The outriggers of Indonesia typically have double outriggers, that is, they have an outrigger on each side of the canoe [2]. This is diagrammed in Figure 13, which is based on images in Adrian Horridge's book [17]. Hornell attributes this to the relatively sheltered waters of the Indonesian archipelago. As outriggers moved into more open water, the single outrigger was structurally safer. By comparison, the double outrigger stands a good chance of suspending the main hull from the outriggers in heavy seas.

[3]A type of Asian boat.

B. Doran's View

Doran's work [7] debates the theory of the seaworthiness of the double outrigger and the notion that it is the earlier version of the technology. Doran bases his analysis on dispersal patterns centered on Indonesia. He claims that the double canoe preceded the single outrigger, which in turn preceded the double outrigger. He claims that Hornell's arguments of double outriggers being less seaworthy than single outriggers are poorly supported by any actual evidence. Instead, the evidence points to the seaworthiness of double outriggers, as they spread into areas that already had single outriggers.

He makes the case that the geographic extent of double outrigger canoes, being a subset of the the geographic extent of single outrigger canoes, indicates that it is a later technology, emanating from the center of invention. (See Figure 12.) Likewise, Doran notes that the practice of shunting rather than tacking – used in Micronesian single outrigger canoes under sail – is a later development.

C. Double Hull versus Outrigger

The issue of using a double hulled canoe versus a single hulled canoe with outrigger can be seen as an issue of ease of manufacture, human interface, and capacity. Double canoes required two very similar tree trunks to be present. Most prized for canoe making in Hawaii were Oregon pines that had fallen into the Pacific and drifted to the islands. In fact, it was common for a log to be stored for years until a matching one arrived at the Hawaiian shores [2], [9]. Outrigger canoes have no such manufacturing issues, since the outrigger will not have any need to match the main hull.

Double hull canoes were large devices, requiring several men to handle properly. Thus, such canoes were inappropriate for individual use. Outriggers were generally small enough for a single person to handle.

Finally, it should be noted that the materials used to strap the two hulls of a double canoe together limited the distance between the hulls. These canoes had a much narrower aspect ratio than their descendants, the modern catamaran and trimaran. Generally speaking, the weight and buoyant forces on the second hull of a double hull canoe were large enough to produce moments to snap the connecting beams if they were too long. The smaller outrigger booms had much less weight and buoyant force, and thus could allow for longer booms.

D. Shunting Versus Tacking

Among the more interesting features of outrigger canoes are the different ways that these canoes were sailed into the wind. While a sailboat cannot sail into the wind directly,

[13].

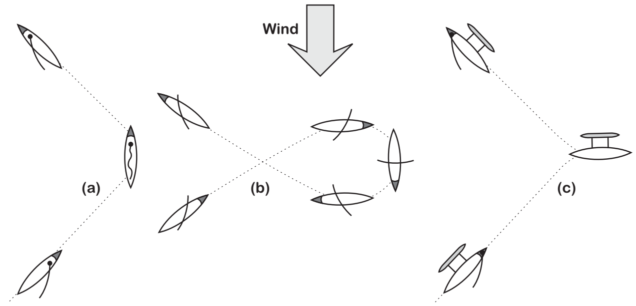

Fig. 14. Sailing into the wind: tacking for a sloop (a), wearing for a square rigger (b), and shunting for an outrigger canoe (c). (From [6], p. 254.)

different sailboats can sail close to the wind – that is – at a diagonal angle into the wind. The issue then becomes one of how to turn the boat to go on the opposite diagonal as one works against the wind. On a modern sailboat, such as a sloop, the boat progresses against the wind by tacking (Figure 14a). In this case, the bow of the boat always is angled into the wind. When the boat turns, the sail goes slack as the boom swings to the other side and the wind fills the sail again. This does not work for a square rigger which at some point in a tack would end up with its sails being pushed backward by the direct wind. Instead, square riggers are turned by a looping method known as wearing (Figure 14b).

Although most of the outrigger canoe sailing against the wind is done by tacking, there is a subset of the outrigger canoes that employ what is known as shunting (Figure 14c). In order to keep the outrigger on the windward side, the Micronesians sail in one direction and then pull to a stop. Since they don't want to have the outrigger on the leeward (away from the wind) side, they change the position of the sail so that the stern is now the bow (longitudinally symmetric boat) and then they zag back that way. Having the outrigger on the leeward side could cause it to plow into the ocean and capsize the boat. Thus, a bias force can push the system out of its stable zone and into a positive feedback situation. They do the shunting to stay in the negative feedback region [6].

This is in contrast to tacking. The front of the boat is still the front of the boat. In tacking, the windward side and leeward side change with every direction change. In the case of shunting, the bow becomes the stern and the stern becomes the bow. To do this, they physically move the mast. Thus, the windward side and the leeward side never change.

Shunting is a relatively recent addition to the sailing techniques. In fact, Doran points out that shunting is done by Micronesians [7], but not by Polynesians, even though both use a single outrigger configuration. Malaysians use double outriggers, which makes shunting useless. Likewise, double canoes (forbearers of modern catamarans) simply tack [7], [13].

VI. Conclusions

Fig. 15. Modern outrigger canoe riding a wave.

When fully considered, the outrigger technology, whether used as a single outrigger, double outrigger, or a double hulled canoe, is truly remarkable. By solving the problem of roll stability for dugout canoes, it dramatically increased the seaworthiness of these craft, allowing the Austronesian people to cross the vast reaches of the Pacific and Indian Oceans. This was done by a Stone Age culture with no written language, no metal working, and no plank-built boats. As a best estimate, this feedback mechanism predates the water clock by at least 1000 years. Furthermore, while the water clock was an interesting exercise, it did not achieve a broad penetration into society as a timekeeping device. That task would be performed by the mechanical clock. The outrigger, however, by dramatically increasing the sea worthiness of the Austronesian canoes, bears at least part of the responsibility for the broad colonization of islands from Madagascar to Polynesia, and by that respect, to the very existence of the Polynesian people.

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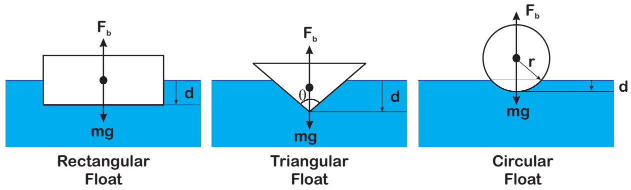

Fig. 16. Different float shapes yield different error equations.

Appendix: Calculation of Buoyant Forces for Various Float Shapes

Qualitatively, the operation of the outrigger is rather simple. When the canoe rotates so as to raise the boom from the water, it's weight at the end of a moment arm provides torque to rotate the boom back to the surface. When the rotation of the canoe acts to push the boom into the water, the buoyancy of the boom acts to restore the boom to the surface of the water.

The buoyancy of the float is easy enough to calculate for several of the typical shapes. The first of these, the rectangular float, on the left side of Figure 16 is the simplest to compute an is the one that gives a linear error equation.

$$\Sigma F_y = F_b - W = 0. \tag{11}$$

For a float with a rectangular cross section and area, a, the weight of the float, mg equals the weight of the displaced water:

$$F_b = mg = V_{imm}\rho g, \tag{12}$$

where V_{imm} is the volume of the immersed portion of the float, i.e.

$$V_{imm} = A_b d, \tag{13}$$

where A_b is the area of the boat bottom, d is the depth of immersion, ρ is the density of water, and g is the acceleration due to gravity.

Now, let's assume that the depth of the float is disturbed away from the nominal, d, by Δd:

$$\begin{aligned} \Sigma F_y &= F_b - W = F_{\Delta d} & (14)\\ &= \rho g(d + \Delta d)A_b - mg & (15)\\ &= \rho g d A_b - mg + \rho g \Delta d & (16)\end{aligned}$$

Since the first two terms cancel in equilibrium, we arrive at the resultant buoyant force as a result of the vertical displacement is

$$F_{\Delta d} = \rho g \Delta d. \tag{17}$$

In other words, the float resists any change away from equilibrium as expected.

A rectangular cross section on a float is convenient for calculation as it leads to a linear error equation (Equation 17). However, it is less likely that a triangular cross section or a circular cross section, at the center and right of Figure 16, respectively.

For the cross section in the shape of an isosceles triangle, we would like to calculate the buoyancy as a function of the depth of the section, d. Applying Equation 12 again, we have

$$V_{imm} = A_d l, \tag{18}$$

where l is the length of the float into the page and A_d is the area of the submerged triangular cross section as a function of d.

$$A_d = \frac{1}{2} bd, \tag{19}$$

where b is the base of the triangle. We can calculate this from the angle of the submerged corner, θ, and the depth, d, by

$$\tan\frac{\theta}{2} = \frac{\frac{b}{2}}{d} \tag{20}$$

so

$$b = 2d\tan\frac{\theta}{2}, \tag{21}$$

and

$$\begin{aligned} A_d &= \frac{1}{2}(2d\tan\frac{\theta}{2})d & (22)\\ &= d^2\tan\frac{\theta}{2}. & (23)\end{aligned}$$

Again, we change the depth away from nominal by

$$A_{d+\Delta d} = (d+\Delta d)^2 \tan\frac{\theta}{2}, \tag{24}$$

so that

$$A_{d+\Delta d} - A_d = (2d\Delta d + (\Delta d)^2)\tan\frac{\theta}{2}. \tag{25}$$

Finally,

$$\begin{aligned} &F_b(d+\Delta d) - F_b(d) \\ &= [V_{imm}(d+\Delta d) - V_{imm}(d)]\,\rho g & (26)\\ &= l\,[A_{d+\Delta d} - A_d]\,\rho g & (27)\\ &= l(2d\Delta d + (\Delta d)^2)\tan\frac{\theta}{2}\rho g, & (28)\end{aligned}$$

where l is the length of the float, θ is the angle of the submerged corder, ρ is the density of water, and g is the acceleration due to gravity. Now, the feedback term is dependent upon the nominal depth, d, and has a quadratic component.

If we repeat the same set of calculations for the circular cross sectional float, we must calculate the area of the submerged segment as a function of the radius, r, and the depth, d.

$$A_{segment}(r,d) = r^2\text{Cos}^{-1}\frac{r-d}{r} - (r-d)\sqrt{2rd-d^2}. \tag{29}$$

when the float rises out of the water, we see that as $d \longrightarrow 0$, both the first and second terms tend to 0. The buoyant force is thus

$$F_b(r,d) = l\left[r^2\text{Cos}^{-1}\frac{r-d}{r} - (r-d)\sqrt{2rd-d^2}\right]\rho g. \tag{30}$$

If we consider d to be the equilibrium depth for a given float material and radius, then the force opposing any displacement, Δd, is

$$\begin{aligned} &F_b(r,d+\Delta d) - F_b(r,d) \\ &= l\left[\left(r^2\text{Cos}^{-1}\frac{r-(d+\Delta d)}{r} - \right.\right. \\ &\quad \left.(r-(d+\Delta d))\sqrt{2r(d+\Delta d)-(d+\Delta d)^2}\right) - \\ &\quad \left.\left(r^2\text{Cos}^{-1}\frac{r-d}{r} - (r-d)\sqrt{2rd-d^2}\right)\right]\rho g. & (31)\end{aligned}$$

For small Δd, Equations 28 and 31 both become linear in Δd, which matches physical intuition.