Unified Motion Planner for Fishes with Various Swimming Styles
Supplemental Document

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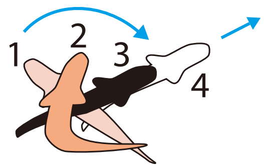

Figure 1: *View from above of the C-start of an archerfish (modified from Figure 2 in [Schuster 2012]).*

1 Detailed Information of Swimming Mechanism in Real Fishes

1.1 Motion Planning Abilities

As a straightforward example of fish instantly conducting motion planning with respect to destination, speed, and swimming style, we focus on the swimming pattern known as C-start.

When attacked by an enemy while resting, fish and amphibians instantaneously bend their bodies in the shape of the letter C to escape (Figure 1). Depending on whether the stimulus comes from the right or left, a fish or amphibian can aptly escape an enemy by reflexively contracting the muscles on either the right or left side of its body. This kind of escape action is called C-start [Domenici and Blake 1997]. Regarding C-start, many studies have been conducted in neurosciences [Korn and Faber 2005], and it is currently accepted that the Mauthner cells located in the hindbrain of fish are important.

A type of quick-start swimming such as C-start is observed not only in passive escape but also in proactive actions, such as social interactions or predator strikes [Domenici and Blake 1997; Schriefer and Hale 2004]. In particular, Schuster et al. studied in detail the brain mechanism of archerfish, a hunting fish species [Schuster 2010; Schuster 2012]. According to Schuster et al., after first observing the movement of their prey, archerfish are able to instantly decide on when and where to move, in what direction to swim, and how much power to exert upon beginning to swim [Wohl and Schuster 2007; Schlegel and Schuster 2008]. In terms of similar behavior, machaca, a South American freshwater fish species that is known to eat fruits that fall in the water, consider the effect of river currents and control their strength in order to reach fruits [Krupczynski and Schuster 2008].

1.2 Swimming Modes

In the field of fish physiology, the Lindsey classification of the swimming styles of various fish to 12 types is widely known [Lindsey 1978]. We call these 12 types of swimming styles “swimming modes.” The classification chart for swimming modes is shown in Figure 2. In Figure 2, the vertical axis represents the types of primary movements, and the horizontal axis represents the breadth of the primary movements’ regions, expressing the differences in characteristics of the swimming motions of various fish in a way that is easy to understand.

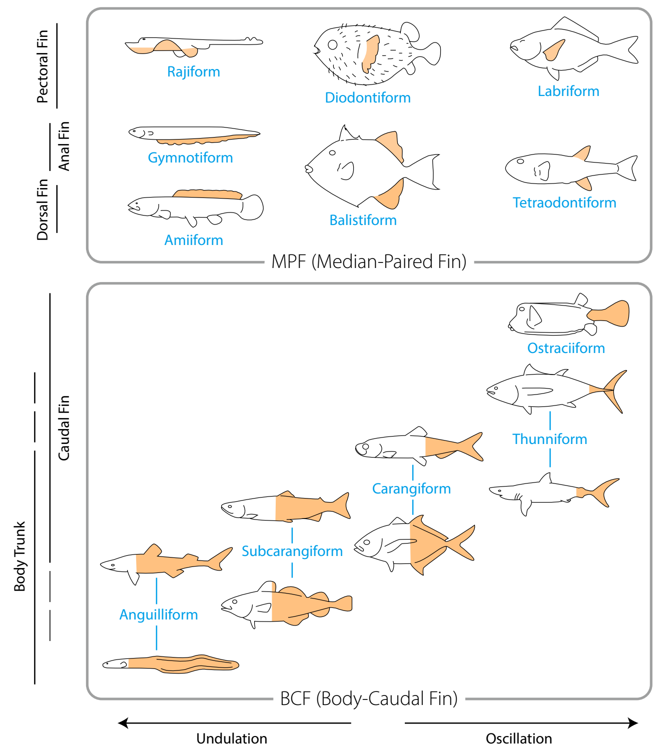

Figure 2: *12 types of swimming modes. The orange areas denote the primary movement regions. The vertical axis represents the types of primary movements and the horizontal axis represents the breadth of the primary movement regions. Line drawings are from [Lindsey 1978].*

Oscillation and undulation are two types of movements that describe fins or body movement. As shown in Figure 2, the tendency to use undulation increases as the movement region increases and the tendency to use oscillation is stronger as the movement region decreases.

In addition, swimming modes are largely divided into two groups. The first group is called Body-Caudal Fin (BCF), wherein the section from the body trunk to the caudal fin is moved. The second is called Median-Paired Fin (MPF), wherein the fins that are central or paired leftright are moved [Sfakiotakis et al. 1999; Blake 2004].

BCF comprises the following five swimming modes.

1. Anguilliform: A large undulating region, spanning from body trunk to the caudal fin; it is observed in eels and most types of sharks.

2. Subcarangiform: Along with the Carangiform, it is between the Anguilliform and Thunniform and is slightly closer to the Anguilliform. It is observed in trout, cod, etc.

3. Carangiform: Along with the Subcarangiform, it is between

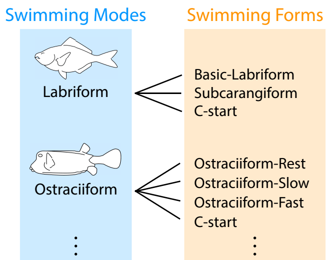

Figure 3: *Relation between swimming modes and swimming forms.*

the Anguilliform and Thunniform, and slightly closer to the Thunniform. It is observed in jacks, herrings, etc.

4. Thunniform: Only the region close to the caudal fin undulates. It is observed in tunas, billfishes, etc.

5. Ostraciiform: Only the region close to the caudal fin oscillates. It is observed in boxfish, torpedo rays, etc.

MPF comprises the following seven swimming modes.

6. Amiiform: The long belt-shaped dorsal fin undulates. It is observed in bowfins, etc.

7. Gymnotiform: The long belt-shaped anal fin undulates. It is observed in knifefish, etc.

8. Balistiform: The dorsal and anal fins undulate. It is observed in triggerfishes, etc.

9. Tetraodontiform: The dorsal and anal fins oscillate. It is observed in ocean sunfish, etc.

10. Rajiform: The giant pectoral fins that connect to the head undulate. It is observed in rays, mantas, etc.

11. Diodontiform: The somewhat large pectoral fins undulate. It is observed in porcupine fish, etc.

12. Labriform: The pectoral fins oscillate. It is observed in wrasses, surfperch, etc.

1.3 Swimming Forms

Up to this point, we have mentioned the cases where fish change their style of swimming based on the situation or speed. We call swimming styles that can change according to the situation “swimming forms.” As shown in Figure 3, a number of “swimming forms” are contained in the “swimming modes.”

As can be seen in Figure 3, out of the 12 types of swimming modes, the Ostraciiform fish greatly change their swimming form.

An example of Labriform fish is *Notothenia neglecta*, a species of wrasse. When swimming at slow speeds, this fish species swims in the basic Labriform style, oscillating the pectoral fins to move forward. In cases where it is necessary to swim fast, e.g., escaping from an enemy, it moves forward by undulating the section that spans from its body trunk to the caudal fin. In other words, its swimming style shifts to Subcarangiform [Archer and Johnston 1989].

An example of an Ostraciiform fish is *Ostracion meleagris*, a boxfish species. This species swims using only its pectoral and anal fins when its body length per second (BL/s) speed is less than or equal to one. For BL/s values between one and five, it also begins to use its dorsal fin and increases the oscillation of its fins as it increases speed. When the BL/s is greater than five and to stabilize its posture, it begins to move its caudal fin intermittently [Hove et al. 2001].

In the proposed method, the swimming modes are treated as attributes specific to each fish species, whereas the swimming forms are treated as states that change over time. For example, a virtual fish with the Labriform swimming mode will always choose from the following three types of swimming forms: Basic-Labriform, Subcarangiform, and C-start. Our virtual fish swim by either switching their swimming form or maintaining the same swimming form over time.

1.4 Speeds and Switching Muscles

Many fish swim using two types of muscles, red and white, depending upon the required intensity of an action [Rayner and Keenan 1967; Hudson 1973; Bone et al. 1978; Tsukamoto 1984a; Tsukamoto 1984b]. In general, red muscles are small and well-suited for sustained movement. White muscles are large and well-suited for quick movement. As an example, a yellowtail is shown in Figure 4.

Tsukamoto measured physiological parameters, such as muscle output and consumed oxygen volume, for yellowtail swimming inside a water tunnel [Tsukamoto 1984a]. The red muscles were active regardless of the swimming speed, whereas the white muscles were active only in the middle- and high-speed range. In addition, when reaching a particular speed, the output from the red muscles started to decrease and the yellowtail switched to the white muscles. The speed value at which the white muscles start to become active is called the Ignition Point of White muscle (IPW), and the speed value at which the red-muscle activity reaches a saturation point and the white muscles become the main part of action is called the Saturation Point of Red muscle (SPR).

Furthermore, the swimming speed range of a fish is classified into three swimming phases with the IPW and the SPR serving as boundaries [Tsukamoto 1984a].

- Sustained Phase: Red muscles are the main part of action. The fish does not tire even after swimming for a significant amount of time.
- Prolonged Phase: Between the sustained and burst phase. The red muscles are still being used and the white muscles start to get used.
- Burst Phase: The white muscles are the main muscles used. The faster the fish swims, the quicker the build-up of fatigue. This swimming phase cannot be maintained for long. Speeding up to the burst phase only occurs in exceptional situations.

The swimming phases reflect the physiology and ecological attributes of a species. For instance, migratory fish, such as the jack mackerel or chub mackerel, have high SPR values. In other words, for these fish, the proportion taken up by the sustained phase and prolonged phase is large; that is, they are good at using their red muscles to swim for long periods. On the other hand, for fish such as carp, which typically lie still and occasionally burst into motion, the IPW and SPR are almost equal. In other words, these fish do not have a prolonged phase and are good at swimming for short periods using their white muscles.

Using the above as a reference, we define the qualitative speed U_Q as (Figure 5) where U_{min}, U_{IPW}, U_{SPR}, and U_{max} are species-

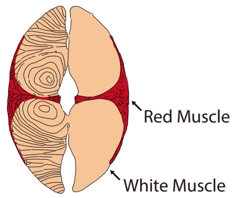

Figure 4: *Cross-sectional view of a yellowtail. The line drawing is from Figure 1 of [Tsukamoto 1984a].*

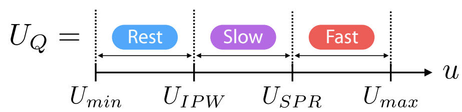

Figure 5: *Correspondence between fish speed u and qualitative speed U_Q.*

specific parameters.

$$U_Q = \begin{cases} [\text{Rest}] & \text{if} \quad U_{min} \leq u < U_{IPW} \\ [\text{Slow}] & \text{if} \quad U_{IPW} \leq u < U_{SPR} \\ [\text{Fast}] & \text{if} \quad U_{SPR} \leq u \leq U_{max} \end{cases} \tag{1}$$

- U_{min} is the minimum speed required for breathing or generating dynamic lift. U_{min} varies greatly depending on fish species or body length [Magnuson 1978]. For many fish, $U_{min} = 0$. However, for several fish species, such as skipjack or Japanese Spanish mackerel, $U_{min} > 0$. These fish lack swim bladders and generally have to swim at a set speed to generate dynamic lift.

- U_{IPW} is a parameter to represent the speed at which the white muscles start to become active.

- U_{SPR} is the previously mentioned SPR. It signifies the maximum speed at which red muscles are the main muscles used and a fish can swim for a long period. Thus, U_{SPR} is also an indicator of the swimming ability of a fish.

- U_{max} represents the maximum possible speed of a fish species. It is defined as the speed that lasts between one second and a few seconds, and it is 10 BL/s in most species [Blaxter 1967].

U_Q is used in the swimming form selection that is explained below. U_{min}, U_{IPW}, U_{SPR}, and U_{max} are the boundary markers used for converting u to U_Q and have the significance of being parameters that determine the motion characteristics of a fish.

2 Definition of Partial Skeleton Model

Figure 6 shows the definition of partial skeleton model for each of the 12 types of swimming modes.

Orange colored joints correspond to Body-PSU, bluegreen colored joints correspond to Plate-PSU, magenta colored joints correspond to Ribbon-PSU, and yellowgreen colored joints correspond to Disk-PSU. The movement of each PSU is independently controlled; hence, it is also possible, as for the pectoral fins of Diodontiform fish, to allot multiple PSUs for one body part.

3 Definition of Swimming Forms

Table 1 lists the definitions of the swimming forms used in this study. The PSU actions corresponding to translational movement are listed in the "Translate" column and the PSU actions corresponding to rotational movement are listed in the "Rotate" column. C-start, in the bottom row, is a definition that is shared by all swimming modes.

In creating these definitions, we used Lindsey's classification of swimming modes [Lindsey 1978]; then, based on human eye observations, we made improvements to reproduce the movements of actual fish. In addition, we referred to [Hove et al. 2001] for the definition of Ostraciiform and [Archer and Johnston 1989] for the definition of Labriform.

4 Rules of Swimming Form Selection

Table 2 lists the swimming form selection rules used in this study. B-Angf. is the basic Anguilliform, Ostf. is Ostraciiform, B-Rajf. is the basic Rajiform, B-Labf. is the basic Labriform, and Subcf. is the Subcarangiform. As for the eight swimming modes not listed in Table 2, the same rules as those for Anguilliform apply, where the basic swimming form and C-start are used.

If U_{Q_t} = [Rest] and $U_{Q_{t+1}}$ = [Fast] and the virtual fish conduct escape action, then the fish will select C-start regardless of the swimming mode. If the fish do not conduct an escape action, the swimming form listed below C-start is selected.

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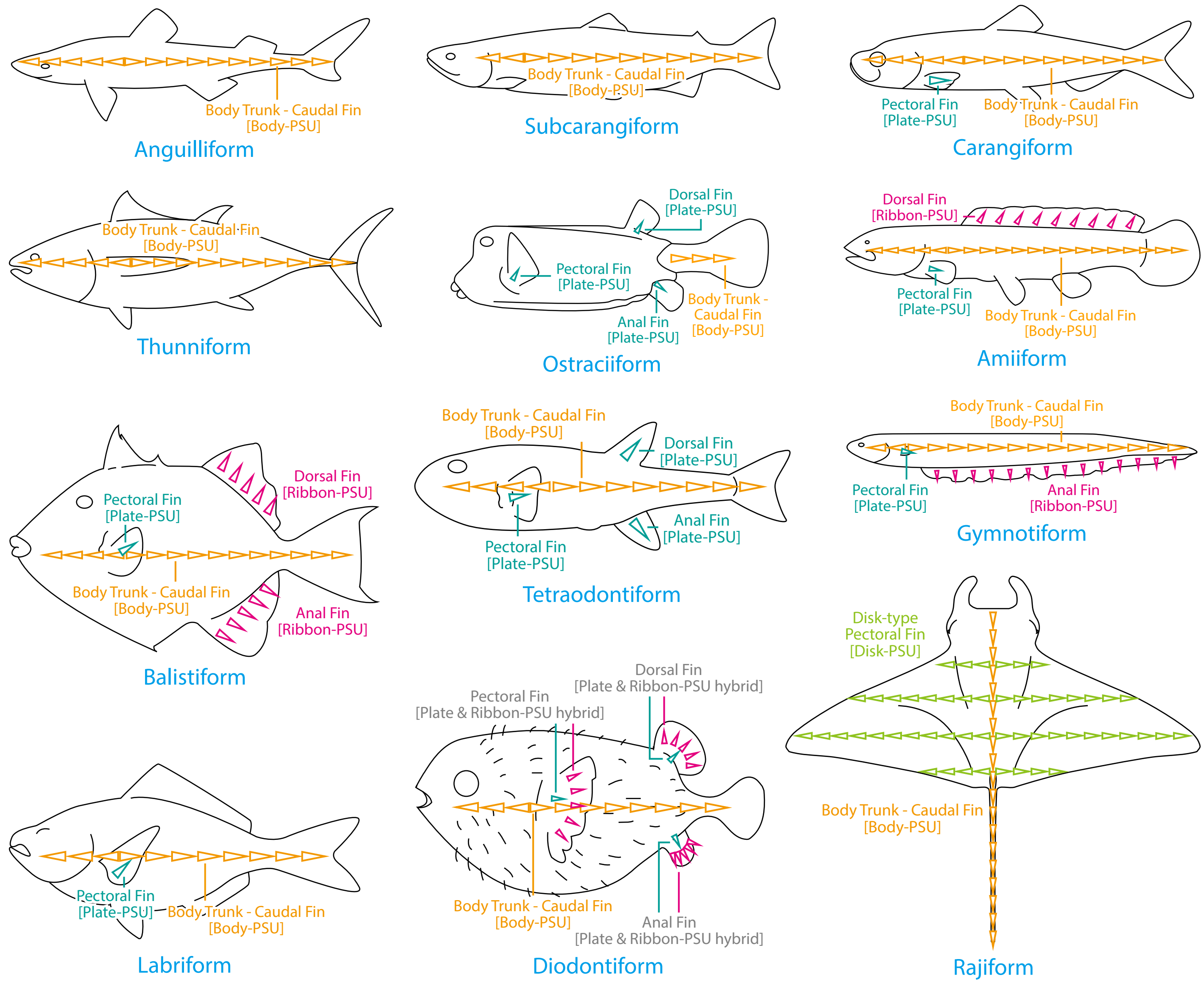

Figure 6: *Partial skeleton model definitions ware used for each of the 12 types of swimming modes.*

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Table 1: *List of swimming form definitions.*

Swimming Mode	Swimming Form	Translate	Rotate
Anguilliform	Basic-Anguilliform	Undulate Body-PSU	Bow-like bend Body-PSU
Subcarangiform	Basic-Subcarangiform	Undulate Body-PSU	Bow-like bend Body-PSU
Carangiform	Basic-Carangiform	Undulate Body-PSU	Bow-like bend Body-PSU
Thunniform	Basic-Thunniform	Undulate Body-PSU	Bow-like bend Body-PSU
Ostraciiform	Ostraciiform-Rest	Oscillate Plate-PSU (Pectoral Fin) Oscillate Plate-PSU (Anal Fin)	Bias oscillate speed of Plate-PSU (Pectoral Fin) Bow-like bend Body-PSU Bend Plate-PSU (Anal Fin) Bend Plate-PSU (Dorsal Fin)
	Ostraciiform-Slow	Oscillate Plate-PSU (Pectoral Fin) Oscillate Plate-PSU (Anal Fin) Oscillate Plate-PSU (Dorsal Fin)	Bias oscillate speed of Plate-PSU (Pectoral Fin) Bow-like bend Body-PSU Bend Plate-PSU (Anal Fin) Bend Plate-PSU (Dorsal Fin)
	Ostraciiform-Fast	Oscillate Plate-PSU (Pectoral Fin) Oscillate Plate-PSU (Anal Fin) Oscillate Plate-PSU (Dorsal Fin) Oscillate Body-PSU	Bias oscillate speed of Plate-PSU (Pectoral Fin) Bow-like bend Body-PSU Bend Plate-PSU (Anal Fin) Bend Plate-PSU (Dorsal Fin)
Amiiform	Basic-Amiiform	Oscillate Body-PSU Oscillate Plate-PSU (Pectoral Fin) Undulate Ribbon-PSU (Dorsal Fin)	Bias oscillate speed of Plate-PSU (Pectoral Fin) Bow-like bend Body-PSU
Gymnotiform	Basic-Gymnotiform	Oscillate Plate-PSU (Pectoral Fin) Undulate Ribbon-PSU (Anal Fin)	Bias oscillate speed of Plate-PSU (Pectoral Fin) Bow-like bend Body-PSU
Balistiform	Basic-Balistiform	Oscillate Plate-PSU (Pectoral Fin) Undulate Ribbon-PSU (Dorsal Fin) Undulate Ribbon-PSU (Anal Fin)	Bias oscillate speed of Plate-PSU (Pectoral Fin) Bow-like bend Body-PSU
Tetraodontiform	Basic-Tetraodontiform	Oscillate Plate-PSU (Pectoral Fin) Oscillate Plate-PSU (Anal Fin) Oscillate Plate-PSU (Dorsal Fin) Oscillate Body-PSU	Bias oscillate speed of Plate-PSU (Pectoral Fin) Bow-like bend Body-PSU Bend Plate-PSU (Anal Fin) Bend Plate-PSU (Dorsal Fin)
Rajiform	Basic-Rajiform	Oscillate Disk-PSU	Bow-like bend Body-PSU Tilt Body-PSU
	Glide	No motion	No motion
Diodontiform	Basic-Diodontiform	Oscillate Plate-PSU (Pectoral Fin) Undulate Ribbon-PSU (Pectoral Fin) Oscillate Plate-PSU (Anal Fin) Undulate Ribbon-PSU (Anal Fin) Oscillate Plate-PSU (Dorsal Fin) Undulate Ribbon-PSU (Dorsal Fin) Oscillate Body-PSU Undulate Ribbon-PSU (Caudal Fin)	Bias oscillate speed of Plate-PSU (Pectoral Fin) Bow-like bend Body-PSU Bend Plate-PSU (Anal Fin) Bend Plate-PSU (Dorsal Fin)
Labriform	Basic-Labriform	Oscillate Plate-PSU (Pectoral Fin)	Bias oscillate speed of Plate-PSU (Pectoral Fin) Bow-like bend Body-PSU
	Subcarangiform	Undulate Body-PSU	Bow-like bend Body-PSU
(General)	C-start	Undulate Body-PSU slightly	Bow-like bend Body-PSU strongly

Table 2: *Rules of swimming form selection.*

U_{Q_t} $\downarrow$ $U_{Q_{t+1}}$	Rest ↓ Rest	Rest ↓ Slow	Rest ↓ Fast	Slow ↓ Rest	Slow ↓ Slow	Slow ↓ Fast	Fast ↓ Rest	Fast ↓ Slow	Fast ↓ Fast
Anguilliform	B-Angf.	B-Angf.	C-start /B-Angf.	B-Angf.	B-Angf.	B-Angf.	B-Angf.	B-Angf.	B-Angf.
Ostraciiform	Ostf.-Rest	Ostf.-Slow	C-start /Ostf.-Fast	Ostf.-Rest	Ostf.-Slow	Ostf.-Fast	Ostf.-Rest	Ostf.-Slow	Ostf.-Fast
Rajiform	B-Rajf. /Glide	B-Rajf. /Glide	C-start /B-Rajf.	B-Rajf. /Glide	B-Rajf. /Glide	B-Rajf.	B-Rajf. /Glide	B-Rajf. /Glide	B-Rajf.
Labriform	B-Labf.	B-Labf.	C-start /Subcf.	B-Labf.	B-Labf.	Subcf.	B-Labf.	B-Labf.	Subcf.