Quantitative understanding of the fly casting stroke through measurements and robotic casting

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Abstract

A stumbling point for many learning to fly fish is being able to fly cast well enough to 'present' a fly to a feeding fish. Even among more skilled fly fishers, learning to fly cast better is often a bottleneck towards advancement in the sport. Fly casting instruction today relies on the visual inspection of the fly casting stroke and the resulting 'loop' of fly line. These qualitative visual cues help fly casting instructors spot the strengths and weakness in a student's casting stroke. We introduce two novel technologies for fly casting instruction that result in a *quantitative* understanding of the fly casting stroke. In particular, we describe a novel robot that is able to replicate standard overhead casts. This achievement is made possible by measuring the casting stroke using a small (MEMS) rate gyro to record the angular velocity of the fly rod in the casting plane. The robot is then programmed to replicate this angular velocity history. Potential uses of this robot include an objective means to assess fly rod, fly line and leader designs, as well as new methods for fly casting instruction.

Keywords: dynamics, fly casting, measurement, MEMS, robotics

Introduction

The sport of fly fishing has enjoyed considerable growth over the last decade, perhaps in part due to the popularity of the film *A River Runs Through It* and the novella (Mclean, 1976) of the same title on which the movie is based. While today's fly fishers may aspire to fish like the fabled characters of this novella, very few actually realise this goal. The most vexing part of fly fishing for beginners is learning how to *cast well* in order to accurately 'present' their fly to a feeding fish, perhaps some 3 to 30 m away. For many fly fishers, fly casting well remains a bottleneck to advancement in the sport.

Fly fishers learn to fly cast through considerable practice and also with the aid of fly casting instructors, classes, videos, and books. Much attention in instruction is given to understanding the dynamics of the fly rod and how the rod is able to cast the long length of attached fly line (see, for example, Kreh, 1974; Krieger, 1987; Wulff, 1987; Jaworowski, 1992; Lord, 2000; Borger, 2001). A properly cast fly line, as shown in Fig. 1, forms a narrow 'loop' that propagates as a nonlinear wave along the length of the line before laying out straight close to the surface of the water.

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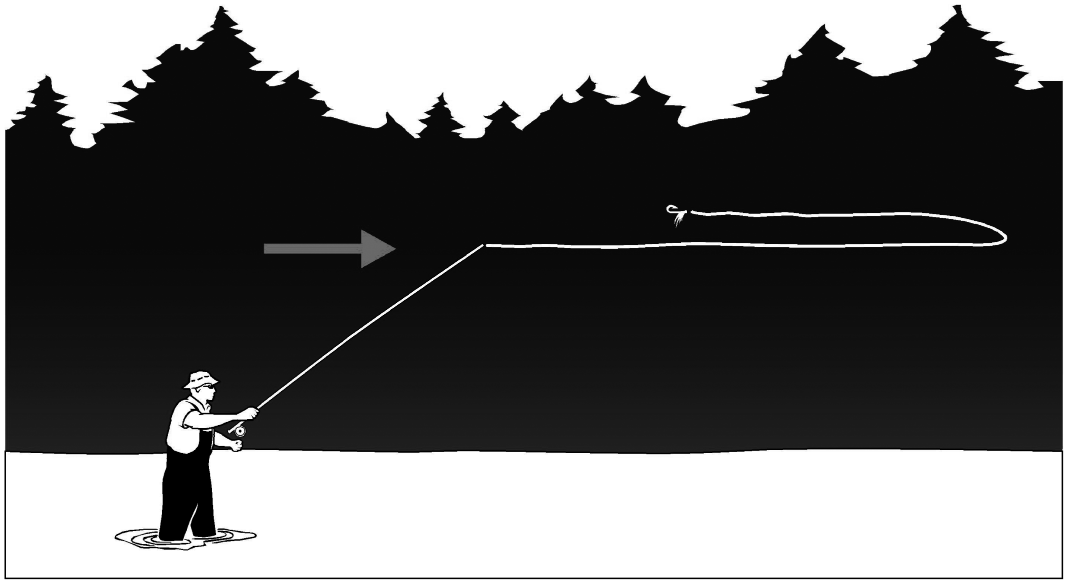

Figure 1 A properly cast fly line forms a distinctive 'loop' during casting. This loop forms between the travelling upper portion of the line and the stationary lower portion.

The motion of the tip of the fly rod is the key 'input' to the fly line, as it controls the size, shape and speed of this loop. In turn, the motion of the caster's hand is the key 'input' to the fly rod. Given the long length of a fly rod (typically 3 m), seemingly subtle changes to the motion of the caster's hand may have a pronounced effect on the motion of the rod tip and hence the loop. This sensitivity underscores the need to develop highly controlled casting strokes in order to become a good fly caster.

The dynamics of fly casting have attracted some attention in the scientific literature, with the major result that computational models now exist for the fly line alone and also the fly line coupled to a flexible fly rod. Models of the fly line alone progress from those that assume a priori that the loop front is either a square or a semi-circle and with assumed dimensions (Spolek, 1986; Lingard, 1988; Robson, 1990; Hoffman & Reth, 1999; Gatti-Bono & Perkins, 2003) to those that compute the loop shape and size from the governing equations of motion that account for aerodynamic drag, fly line weight, and inertia (Robson, 1990; Hendry & Hubbard, 2000; Watenabe, 2002; Gatti-Bono & Perkins, 2002, 2003, 2004a). The governing equations follow from either finite element or lumped parameter approximations (Robson, 1990; Hendry & Hubbard, 2000; Watenabe, 2002), or from the fundamental continuum models of the fly line (Gatti-Bono & Perkins, 2002, 2003, 2004a). The continuum models also capture realistic fly line taper, tension, and (small) bending. The nonlinear dynamics of the fly line coupled to the dynamics of a flexible fly rod have been studied using both finite differencing (Gatti-Bono & Perkins, 2004a) and finite element discretisation (Hendry & Hubbard, 2002), and both with good predictions (within 10%) of experimental measurements.

The future utility of such modelling and simulation tools in the design of fly rods and lines is predicted by Phillips (2000) who states a 'few innovations that could be on the horizon' include 'simulation of fly casting, showing how changes in rod design affect the geometry of the cast.' Phillips also predicts that the fly fishing industry 'could be well served by the development of a programmable [fly] casting robot, designed to reproduce the casting motions of a broad range of fly-fishers.' He draws a parallel with the golf industry's success in developing a golfing robot (the 'Iron Byron') and the impact that this one development has had on golf equipment design, testing and standards. This thought provided impetus for the study described here.

Our objective is to describe a programmable robot that can successfully fly cast and which, to the authors' knowledge, is the first such robot that has succeeded in achieving this goal. The success follows from the quantitative definition of the casting strokes made possible by electronically measuring the casting strokes of (human) fly casters. The casting strokes are quantified in Section 2, and a description of the robot and controller follow in Section 3. We describe results and the performance of the robot in Section 4, prior to drawing conclusions.

Quantifying the casting strokes

The casting strokes in standard overhead fly casting consist of a sequence of *back casts* and *forward casts* that are separated by distinct pauses. During these pauses, the fly rod is held stationary and the loop propagates (forward or backward) until it eventually 'turns over' when it reaches the end of the fly line. This turnover signals the appropriate time to begin the next casting stroke (either forward cast or back cast). An example forward cast is illustrated in Fig. 2, starting with the line laid out behind the caster (the end of the previous backcast) and ending with the line laid out in front of the caster (loop turnover and the start of the next backcast).

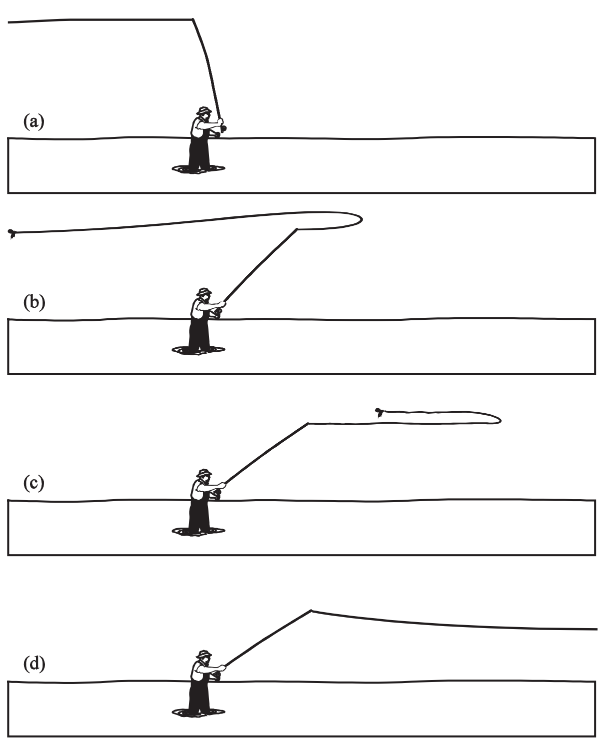

Figure 2 (a) End of back cast with line laid out behind caster; (b) loop forms just after caster stops rod in forward cast; (c) loop propagates forward and eventually 'turns over' as in (d).

Fly casting books and videos provide excellent descriptions of the casting strokes and they offer helpful advice on how to learn or improve fly casting techniques (see, for example, Kreh, 1974; Krieger, 1987; Wulff, 1987; Jaworowski, 1992; Lord, 2000; Borger, 2001 and the many other references cited there). Our understanding of these strokes has also increased through careful photographic studies that clearly show the flexible motion of the fly rod (Mosser & Buchman, 1980; Walker, 1985). Quantitative measurements of the casting stroke, however, have only recently been made (Bonner, 2003; Perkins & Richards, 2003) and these now enable the development and control of a programmable fly casting robot.

During casting, the fly rod moves largely in one plane and the movement is dominated by *rotation.* This fact is emphasised in Fig. 3 which illustrates the motion of the rod from one extreme position (left) to the other extreme (right) during one casting stroke. Notice that the rotation of the rod creates a displacement of the rod tip that that is many times larger than that created by translating the rod grip (hence the mechanical advantage of casting with a long fly rod). Note also that there is no fixed axis of rotation; that is, the instantaneous centre of zero velocity moves modestly during the stroke.

A means of measuring the rod rotation during the casting stroke is depicted in Fig. 4, which illustrates a small (MEMS) rate gyro attached to the butt end of the fly rod with the output collected on a hand-held computer. The rate gyro outputs an analogue voltage

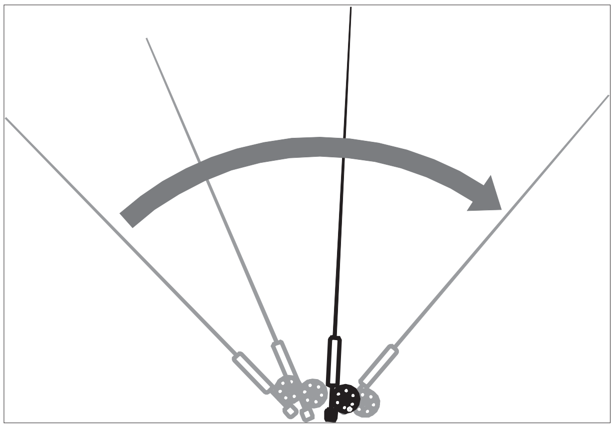

Figure 3 Schematic of one forward casting stroke showing both the rotation of the fly rod (dominant) and the translation of the rod grip (minor).

Figure 4 A small (MEMS) rate gyro that measures the angular velocity of the fly rod at the butt end of the rod and in the plane of the fly cast.

that is proportional to the angular velocity of the butt end of the fly rod as measured in the plane of the fly cast. (The MEMS rate gyro can readily be calibrated by either comparing the output to that of a 'standard' rate gyro or by using published values of the DC offset and sensitivity reported by the manufacturer.) Recording this signal while casting produces an electronic 'casting signature' that is unique to each fly caster and also measures her/his skill level. The differences between casting skill levels become readily apparent when viewing these signatures.

Below we discuss the differences between an expert, an intermediate and a beginner fly caster. The expert caster is a world-renowned fly casting instructor, the intermediate caster is a long-time fly fisher with no professional fly casting training, and the beginner caster is a person casting for the first time following a short (5 min) introduction.

Figure 5 shows the measured angular velocity for two casting cycles as made by an expert caster. Positive values of angular velocity designate the forward cast while negative values designate the back cast. Inspection of this plot reveals several important conclusions. First, there is remarkable *symmetry* in the forward and back casts, with the peak angular velocities within each differing by a mere 5%. In addition, the standard deviation of the peak values is less than 5% of their average for the expert, indicating a highly repeatable casting stroke. Second, both the forward and back casts begin with the same *smooth* increase in angular velocity (modest angular acceleration), followed by a quick 'stop' (large angular deceleration). The stops are followed by a 'rebound' during which the fly rod flexes (vibrates in fundamental bending mode), providing a reaction moment on the caster's hand. The amount of this rebound is indicative of how much the fly rod flexed as the caster 'loads' the rod during casting, and good casters load the rod significantly while casting long distances. The loop is formed during the stop and the best loops are formed by a well defined stop (i.e. very large angular deceleration). Fly casters recognise the best loops as those with the smallest width (or diameter), as they provide less projected area in the flow and therefore less aerodynamic drag. Such small loops are a distinct advantage when casting into a head wind and when casting for distance. The ability to stop the rod abruptly, particularly in the back cast, is the hallmark of an expert fly caster.

The signature of an expert (Fig. 5) is readily distinguished from those of intermediate and beginning fly casters illustrated in Fig. 6. The signature of the intermediate fly caster is very unsymmetrical, with the peak angular velocity in the forward casts exceeding that of the back casts by over 40%. The forward and back cast peaks, however, are nearly as consistent as those of the expert (standard deviations only slightly greater than 5% of the means), indicating a highly repeatable/practised stroke. Note however that the stop in the back cast is not well defined (there is far less angular deceleration compared with that of the forward cast), leading to poor loop formation in the back cast. In addition, the rod rotates *slowly forward* just after each back cast, producing what casting experts call 'rod creep' (note a small positive angular velocity in this region). Rod creep ultimately reduces the available space (casting arc) for applying power in the forward cast. To compensate, this caster then overpowers the rod during the forward cast in achieving a peak angular velocity

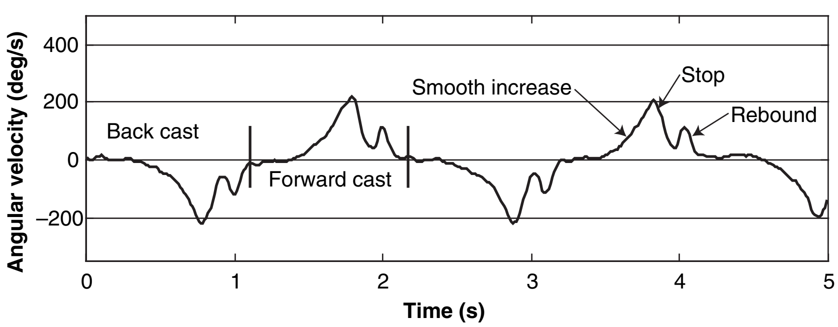

Figure 5 The signature of an expert fly caster. Angular velocity of butt end of fly rod for two casting cycles.

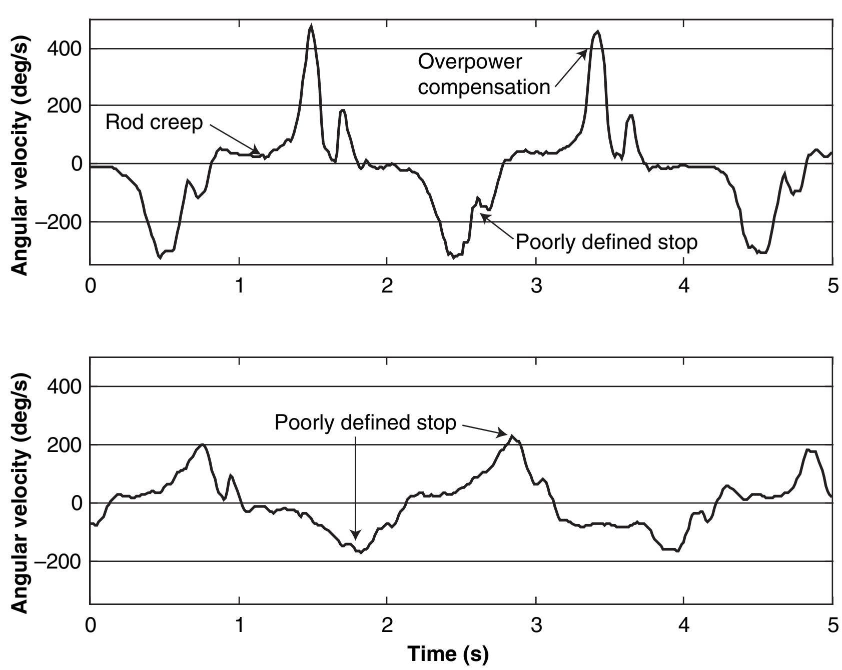

Figure 6 The signatures of intermediate and beginner fly casters using same rod and line length as expert.

nearly 100% greater than that of the expert. Two practical problems result from these casting mistakes. First, the intermediate caster will tire far more quickly than the expert; the intermediate caster generates approximately four times the peak kinetic energy compared with the expert. Second, the loops that result are also likely to close upon themselves in forming what fly casters call a 'tailing loop'. Tailing loops are the bane of fly casters in that they create knots and tangles in the 'leader' that attaches the fly to the fly line.

The signature of a beginner shows a high degree of variability from cast to cast, as might be expected from someone who is learning for the first time the fine motor control and muscle memory needed for fly casting. In particular, the standard deviation of the peak values often exceeds 20% of the average values. Overall, the stops in the back cast and the forward casts are very poorly defined and are characterised by angular decelerations that are at least an order of magnitude less than those of the expert.

The example signatures above demonstrate several key features that define the casting strokes. First, expert casters produce the same angular velocity signature (albeit in opposite directions) for the forward cast and the back cast, a fact exhibited by the remarkable symmetry in Fig. 5. Second, each stroke (forward and back) begins with an approximately parabolic increase in speed that produces what casting instructors emphasise as a 'smooth application of power'. Third, following the peak angular velocity, there is a very large angular acceleration that forms 'the stop'. Fourth, the stop is immediately followed by a significant 'rebound' that serves to dissipate rod vibration caused by the stop. These four main characteristics are quantitative metrics of the casting strokes that can be used for the control of a fly casting robot as described next. These same metrics can also be used to advantage in fly casting instruction.

Fly casting robot: design and control

A robot that can repeatedly cast like a human fly caster opens up new capabilities for the design and evaluation of fly casting equipment (fly rods, fly lines and leaders). Moreover, such a robot, if also programmable, provides a novel platform for fly casting instruction as it can be used to replicate casts of experts and non-experts alike. One design of a fly casting robot is illustrated in Fig. 7.

This robot duplicates each casting signature (angular velocity history) with a high degree of accuracy and then repeats that same signature to produce a continuous train of forward and back casts (as in 'false casting' practice). The rotation of the fly rod is the dominant input in fly casting and therefore the robot is designed with a single degree of freedom. The fixed axis of rotation of the robot is selected to correspond to the approximate location of a fly caster's elbow as if the caster were casting with their elbow held stationary. While this is not necessarily a comfortable way to fly cast, it is certainly possible to achieve short to modest length casts (up to 15 m or so) using this added constraint.

The fly rod is gripped by an arm that is cantilevered from the large visible timing gear in the figure. The timing gear is driven by a cogged timing belt through a pinion mounted on the output shaft of a motor. These major components are also shown in the exploded assembling drawing of Fig. 8. A large commercial stepper motor serves as the actuator and can achieve angular velocities up to 800 deg/s and angular accelerations up to 5000 deg s^{-2}, which are both at the high end of what expert fly casters generate. The large holding torque of 22.0 N m of the stepper motor provides large decelerations at the 'stop' while maintaining position during the remainder of the cast without loss of steps.

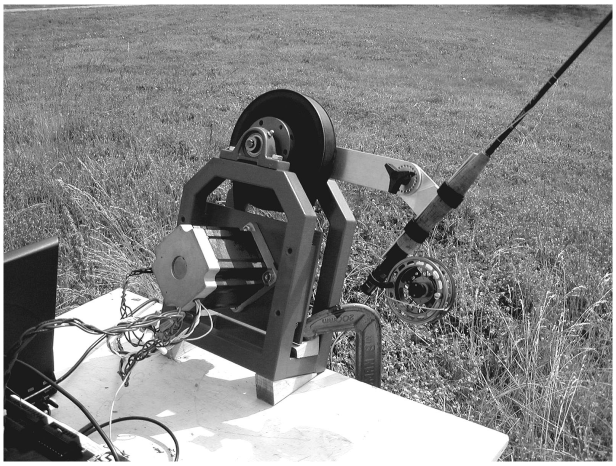

Figure 7 Single degree-of-freedom fly casting robot driven by large stepper motor and motor controller.

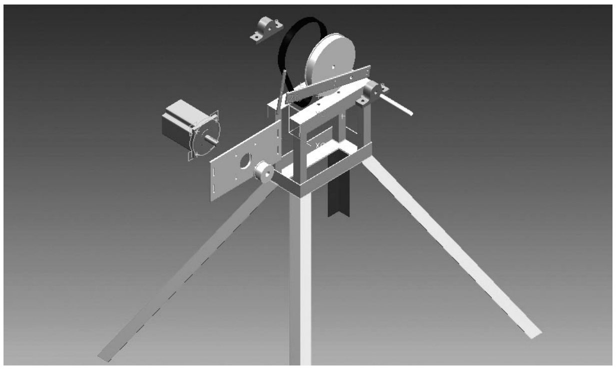

Figure 8 Exploded assembly drawing of principal hardware used to construct the fly casting robot including a stepper motor, pinion, cogged timing belt, timing pulley, arm and supporting bearings, arbor, and frame.

A commercial stepper controller is used to drive the robot, which uses angular velocity and angular acceleration control inputs. The 'motion scheduling mode' is selected that requires no feedback from the attached sensors (rate gyro and motor encoder). The controller is able to track position by maintaining step count with an angular precision of half of a degree. Program commands are issued via a personal computer over an RS-232 serial port. The casting stroke, when encapsulated in a controller program, is stored in the controller memory, and the issued motion commands are output at a rate of 40 Hz. Prior experience measuring fly casting signatures has shown that a 40 Hz sampling rate is sufficiently fast to resolve the principal features of the fly casting strokes as described in Section 2 and as also illustrated in Fig. 9.

We developed specialised software to automate the conversion of casting signature data into controller commands. To this end, the angular velocity history shown in Fig. 9 is discretised into ten 'control points' (shown by solid symbols in Fig. 9) that capture the principal parts of the casting stroke. These include the 'smooth increase' in angular velocity at the start of a stroke (via points 1–3 when numbered from the left), the abrupt 'stop' (points 3–5), the 'rebound' (points 5–9), and the final 'rest' (points 9 and 10). Quadratic interpolation is used between sets of three control points [{1–3}, {3–5}, {5–7} and {7–9}] to create a smooth signature and to maintain constant jerk within the 'smooth increase', 'stop' and 'rebound' parts of the stroke. A linear interpolation at zero angular velocity defines the final 'rest'. Characterising the casting signature using 'control points' allows for quick coding and easy distinction of casting strokes. For instance, variations in casting strokes can be generated and tested swiftly by simply shifting the positions of these control points.

Results and performance

The first results pertain to a modest length cast of 7.6 m (25 ft) of fly line and leader measured from the rod tip as made by an expert fly caster. The associated angular velocity history is shown in Fig. 9. This data was converted to a robot command code using the software described above. The rate gyro shown in Fig. 4 was attached to the butt section of the fly

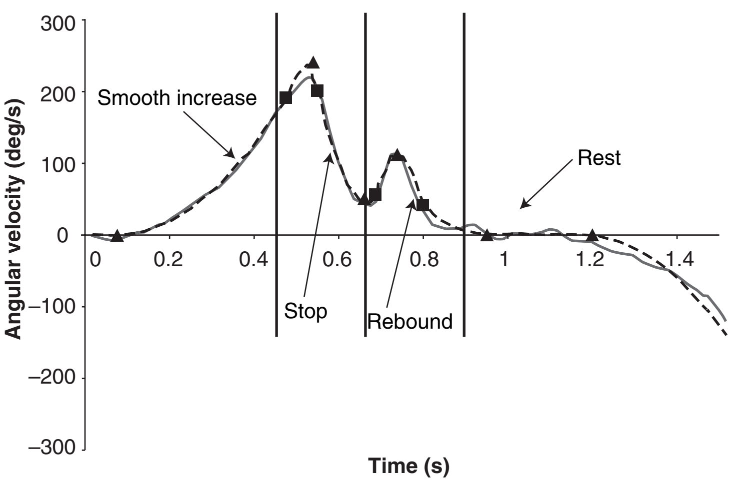

Figure 9 Ten control points are used to characterise the casting signature and to interpolate a smooth curve as a basis for robot input. The casting stroke consists of four principal parts: 1) smooth increase, 2) stop, 3) rebound, and 4) rest. The solid line represents the measured casting signature of an expert caster, while the dotted line is the signature interpolated from the control points and used as the control input to the robot. This example cast is with 7.6 m (25 ft) of line measured from the rod tip.

rod in order to measure the angular velocity history realised by the robot. Doing so provides the means to quantify the accuracy of the controller software and hardware.

Figure 10 illustrates the angular velocity signature input to the controller and the final output measured from the robot. The root-mean-square error between the input and output is 26.9 deg/s over one complete casting cycle. This represents a relative error of 12% when compared to the peak angular velocity (230 deg/s) and 20% when compared to the root-mean-square angular velocity over one cycle (134 deg/s). In addition to these quantitative metrics of performance, it is critical to assess the qualitative characteristics of the resulting loop of flyline and particularly the loop shape and dimensions. Fly casting instructors rely heavily on such visual cues to deduce problems in a student's casting stroke. The dynamics of the loop were recorded using digital video photography and the characteristics of the loop are illustrated in the sequence of still images shown in Fig. 11, where the flyline has been darkened for better contrast. The first image (Fig. 11a) depicts the rod during the 'rebound' phase after the stop. Here, the rod is bending forwards and the loop is just starting to form. The next image (Fig. 11b) shows the completed loop that then propagates as shown (Fig. 11c). The final image (Fig. 11d) shows the loop near the end of the forward cast where it is about to 'turnover'. Overall, the diameter of this loop is very small (approximately 20 cm) as expected from the highly practised cast made by the expert fly caster. Moreover, the loop front is slightly asymmetrical, with more curvature on the top than on the bottom. This asymmetry results in a net positive angle of attack for this loop and this generates a drag force with a positive (upwards) component (Gatti & Perkins, 2004b). Expert casters are able to generate this loop shape intentionally and they note the added distance that results from the added lift. These important qualitative characteristics (loop size and shape) produced by the robot are precisely the characteristics that one expects to see for an expert fly caster.

A similar experiment was conducted for a longer cast of 12.2 m (40 ft) of line measured from the rod tip. As the cast is lengthened, it becomes increasingly important to both measure and control the casting stroke to achieve a well-formed loop and to control longer lengths of line in the air. Figure 12 illustrates the measured (target) angular velocity history for an expert cast together with the control input to the robot. The actual angular velocity output of the robot (not shown) replicates the control signal within a root-mean-square error of 51 deg/s over one complete casting cycle. This represents a relative error of 12% when compared to the peak angular velocity (410 deg/s) and 24% when compared to the root-mean-square angular velocity over one cycle (214 deg/s). As with the shorter cast, the loop for this longer cast is small in diameter (approximately 40 cm) and is largely semi-circular with a slight point at the junction with the top leg.

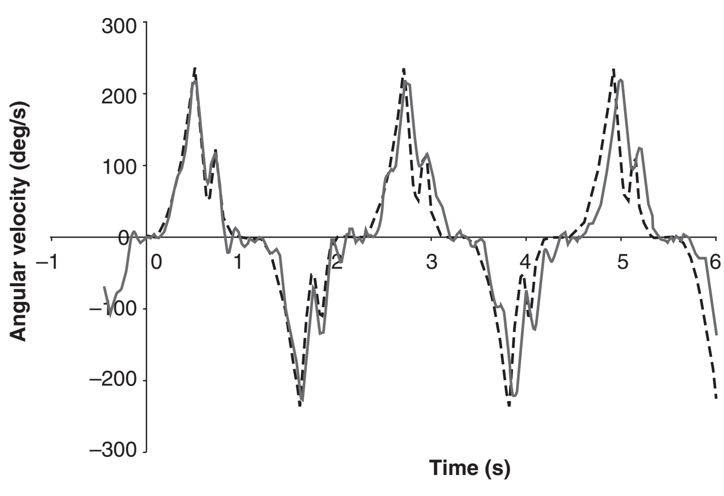

Figure 10 Comparison between robot control signal and robot output for 7.6 m cast. The dashed line represents the angular velocity control input to the robot, while the solid line represents the measured angular velocity output of the fly rod.

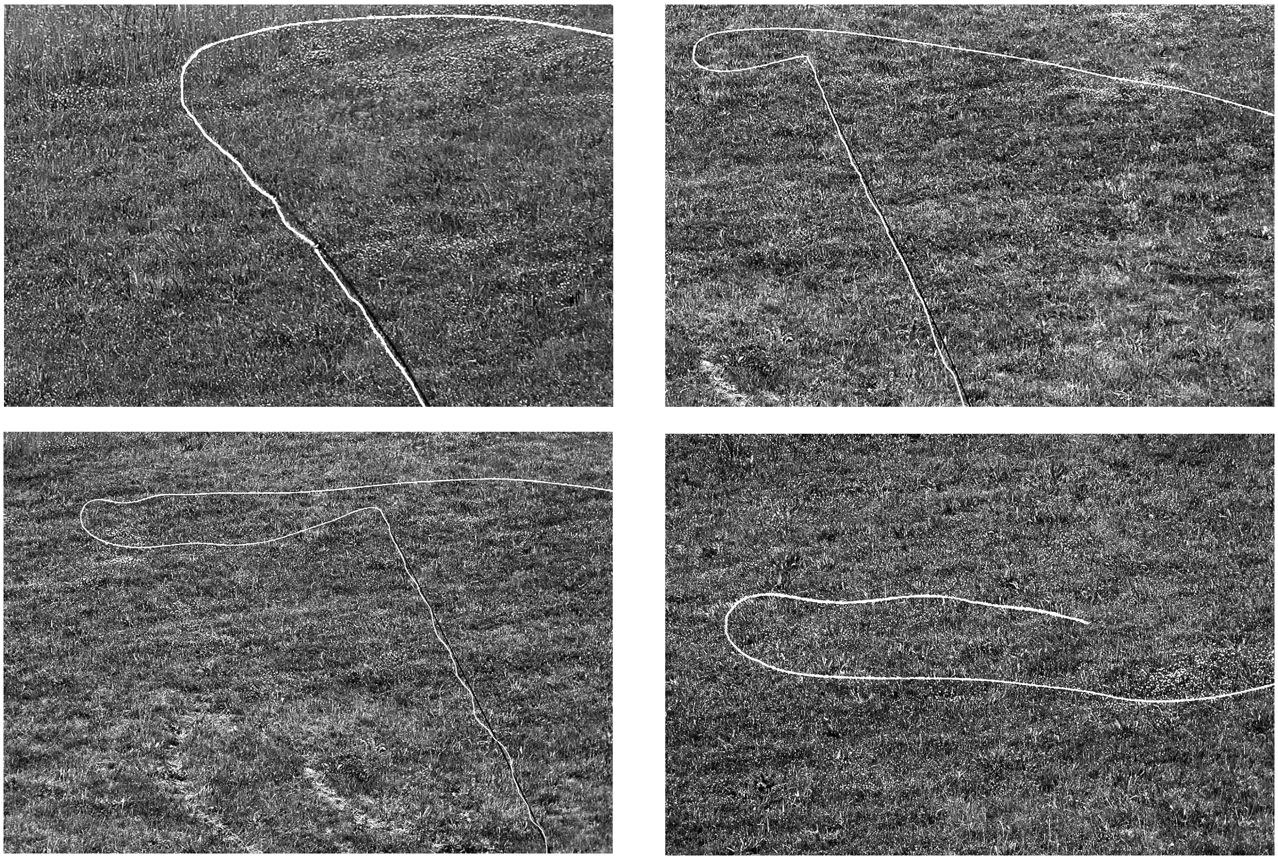

Figure 11 Sequence of still images showing loop shape and dimensions for the 7.6 m cast with input from Fig. 9.
(a) loop is forming during rod rebound after stop;
(b) loop formed a moment later; (c) loop propagation;
(d) loop approaching turnover.

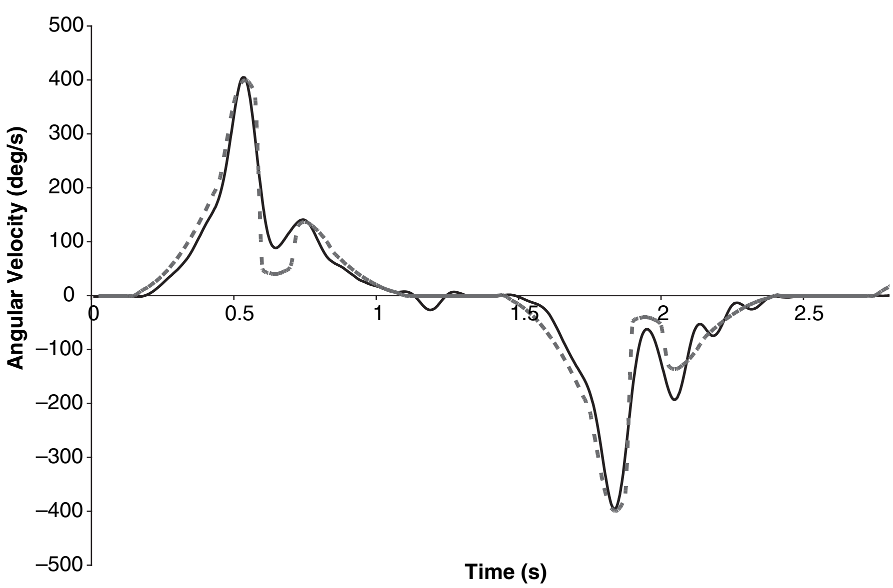

Figure 12 Comparison between robot control signal and robot output for a 12.2 m cast. The dashed line represents the angular velocity control input to the robot, while the solid line represents the measured angular velocity output of the fly rod.

Summary and conclusions

This paper summarises the design and performance of a single-degree-of-freedom robot that can be programmed to successfully fly cast. This is the first such robot known to have succeeded in replicating fly casts. The success derives from a fundamental understanding of the fly casting stroke made possible by using a miniature (MEMS) rate gyro mounted on the fly rod. The measured angular velocity of a fly rod when cast by a human provides the input signal used to replicate the cast by the robot. The actual angular velocity realised by the robot lies within 20% of the target angular velocity as measured by the relative root-mean-square error over a complete casting cycle. The quantitative and qualitative performance of the robot is illustrated with casts of 7.6 m and 12.2 m. The qualitative characteristics of the loop, including the loop diameter and shape, are precisely those expected based on the caster's fly casting skill level.

There are several potential uses for this technology in the future. First, the robot provides a means to achieve a controlled and highly repeatable cast that could be used to evaluate the performance of fly rods and fly lines. Doing so may someday lead to standard objective tests used by the industry for evaluating the performance of fly casting equipment. Second, the robot provides a novel platform for fly casting instruction. It can be programmed to replicate the skill of expert and beginning fly casters alike, and thereby illuminate how the shape and size of the loop are directly related to the principal parts of the casting stroke as defined in Fig. 9. Lastly, the robot might be used to match the natural casting stroke of an individual and to the equipment (notably fly rods) that are best suited to that individual's stroke.

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