Station Keeping Buoy Design Trade-Study Description

Prepared by J. G. Bellingham and A. Hamilton, MBARI

This document outlines the trade-off study to be performed at MBARI to promote an understanding of the design-space relevant to the station keeping buoys envisioned by DARPA for long-term hydrophone support. The current solutions being pursued by the participants of this program were tested during the technology demonstrations held at MBARI in October 2007. The wide range of approaches pursued by the current program participants indicates that the current understanding of the problems and options for developing these systems is not sufficiently understood.

Our goal is to provide an analytical framework that lets us understand how different design approaches might function given realistic environments. In particular, the goal is identify which portions of a very large design space are most promising, with sufficient detail to identify design drivers and optimizations that should be considered. The aim is to give the system designers a basis for aiming future development in a direction that has the highest probability of generating an optimized solution to this difficult engineering problem.

Trade-Study Overview

There are three classes of variables to consider in a design-space investigation;

a. The environmental conditions at the target deployment locations. (wind speed, wave height, and solar insolation.)
b. Variables that affect the performance of the system in given environmental conditions. These variables include those related to what energy sources are utilized, how that energy is collected and stored, and how that energy is applied to keep the buoy on station and performing the needed tasks.
c. Design variables that affect the operational utility of the system. (size, weight, reliability, and cost).

Although there is significant interplay between these three classes, it is useful to consider each individually to minimize competition between the factors that drive the final choices to promote an understanding of the underlying performance issues. For instance, an analysis of the performance factors may drive the design towards a size and weight scale that can not be accommodated, but at least design choices will be made with a clear understanding of the trade-off being made (performance versus size). Similarly, the environmental conditions the system shall operate in will vary from site to site and an understanding of the capabilities of different techniques will aid in designing systems that will be successful across a range of sites.

Present work is focusing on two key enabling elements: a mathematical abstraction for a station keeping buoy that parameterizes key station-keeping buoy characteristics in a way that allows one to relate performance to environmental conditions, and obtaining climatology's for environmental sources of energy and perturbations for potential operational environments.

The goal of the study presented below is to identify which part of the design space should be concentrated on to meet the requirements and to identify optimal design choices related to system performance in a variety of conditions. Coupled with an analysis of environmental conditions at a range of likely deployment sites, it is expected that some optimal design choices will be evident.

Finally, data collected during the October 2007 demonstrations in Monterey Bay may be useful in the context of the design study results, providing a comparison basis for the performance factor analysis.

Trade-Study Outline

To achieve this goal, a number of specific tasks will be undertaken as follows:

Analysis of design space

1. Analysis of environmental conditions at projected sites.
    a. Expected energy fluxes in sun, wind, and waves.
    b. Expected currents
    c. Relative directions of currents, wind and waves
    d. Expected temporal variability of above
2. Analysis of potential energy of various energy sources (solar, wind, wave)
    a. Analysis of possible conversion efficiencies of various sources.
    b. Analysis of energy storage efficiencies.
    c. Analysis of platform energy requirements
        i. Station keeping (depends on environmental conditions)
        ii. Sonar tasks (may depend on station keeping accuracy?)
        iii. Communications
3. Review of operational constraints and form-factor goals.

Design trade-off evaluation

1. Identification of important variables in the design space.
2. Analysis of potential optimization within the range of design space variables.
3. Analysis of sensitivity of trade-offs to deployment site conditions.
4. Effects on trade-space due to limitations imposed by operational/form-factor constraints

Analysis of 2007 demonstration data

1. Analysis of energy harvesting efficiency.
2. Analysis of energy use efficiency.

Example: Station Keep against a Current with Wind Energy in Monterey Bay

For this example we use wind and current data, acquired in Monterey Bay from MBARI's M1 mooring since 1992. The record is not continuous for all sensors, and we limit the study to the portion of the data set in which both the current and wind data is good. The resulting data set has 84903 hourly observations. Figure 1 shows an extract of the data set showing wind speed and direction, and current speed and direction at 20 m depth. The reason we use the 20 m currents rather than surface currents is that the model for the station keeping buoy (described in the next section) has a 50 m hydrophone cable which dominates its drag characteristics. Thus the 20m currents are more representative of the current environment encountered by this particular buoy.

We can compute wind power per unit area by the following formula:

$$P_{wind} = \frac{1}{2}\rho_o v^3$$

For the purposes of the calculations below we approximate the density (ρ_a) of air as 1.168 kg/m^3, ignoring the effects of changing atmospheric temperature, pressure and humidity. The power associated with the prevailing ocean currents is also important, and is calculated using the same formula, using a seawater density (ρ_o) of 1025 kg/ m^3, ignoring variations in salinity and temperature. Figure 2 shows the probability that the current power is below a given level. Thus 90% of the time the current has a power less than 7 W/m^2. Figure 3 provides an equivalent plot for wind power, showing that 90% of the time the wind power is less that 435 W/m^2.

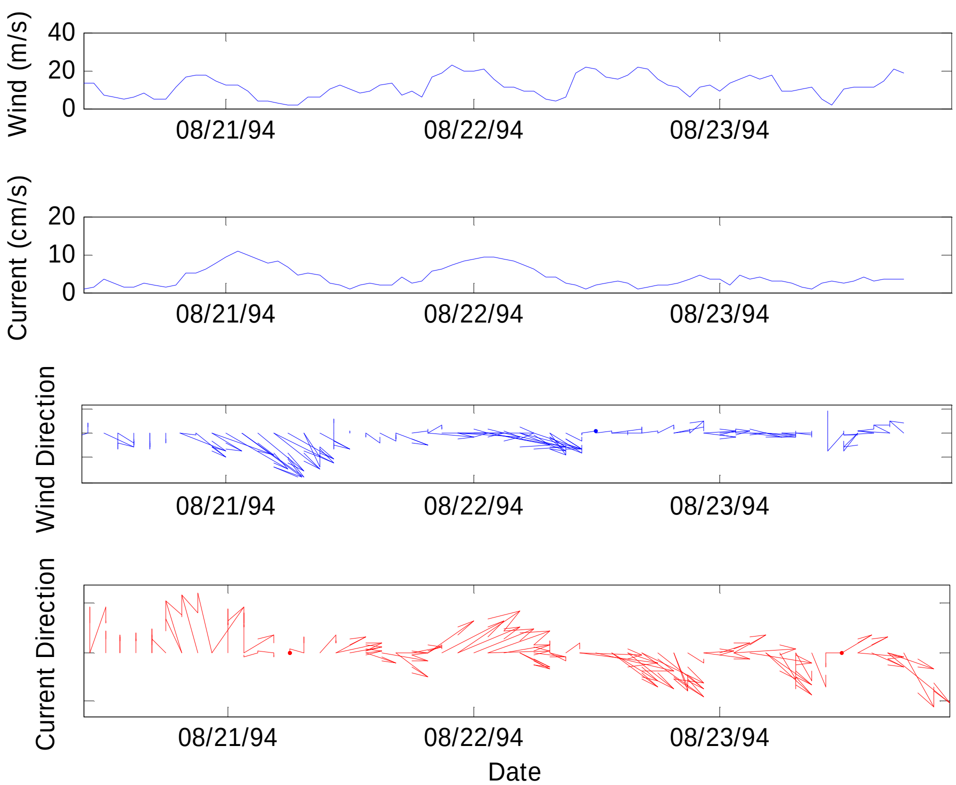

Figure 1: An extract of the M1 data set, showing wind and current speed at 20 m depth, and wind and current direction for a four day period.

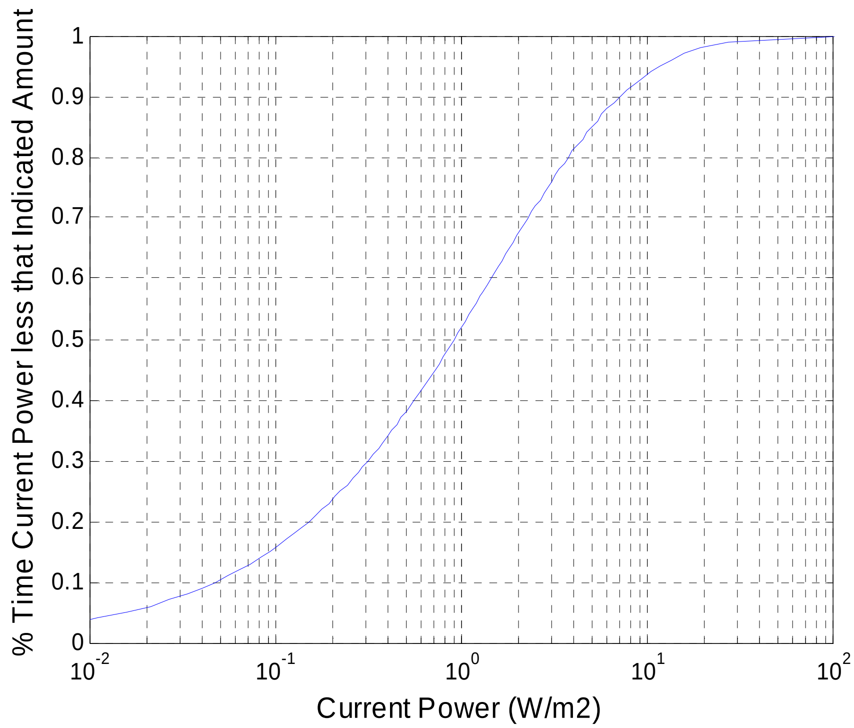

Figure 2: Statistics of current power. This plot shows the fraction of time the current at 20 m depth is less than a given power level.

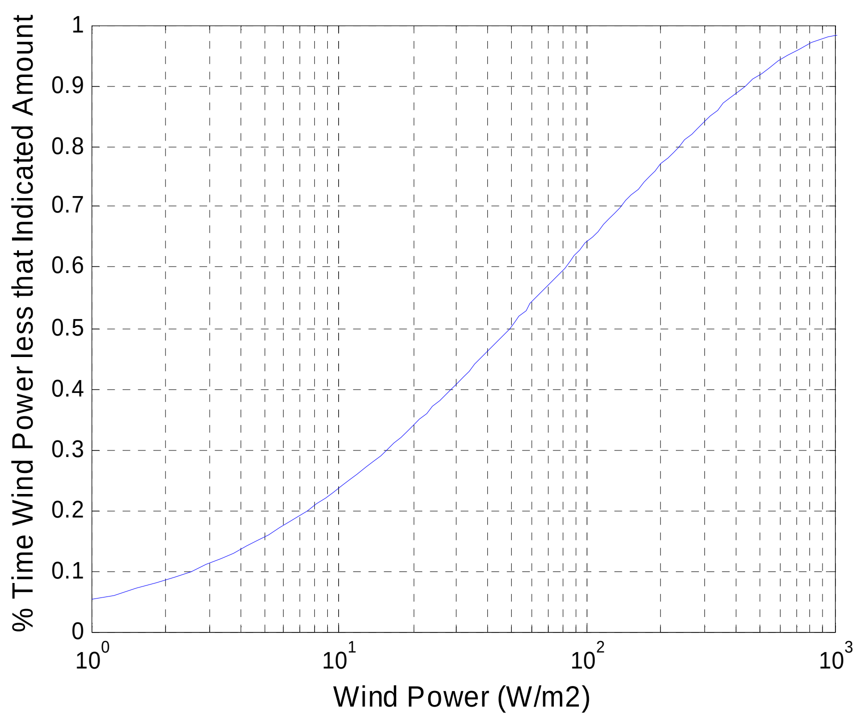

Figure 3: Statistics of wind power. This plot shows the fraction of time the wind is less than a given power level.

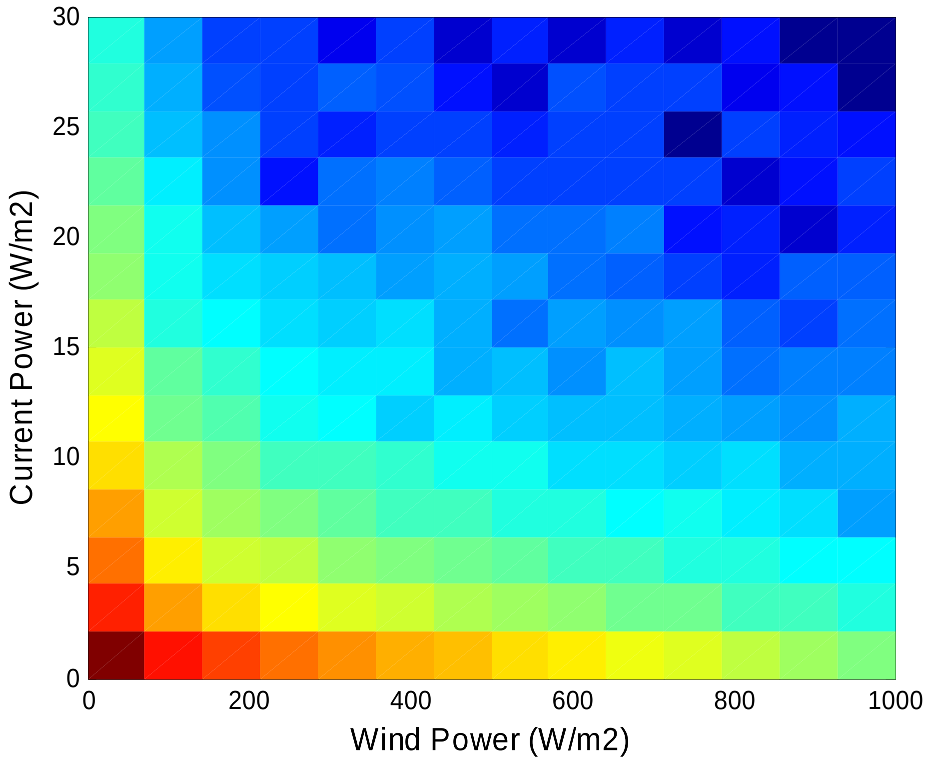

Figure 4: Log probability distribution as a function of both current and wind power. Note that periods of high current power occur most often when winds are low and visa versa.

For the station-keeping buoy, the environment provides both the disturbance (the current) and the source of power to maintain station in the face of the disturbance (in this case wind). An important question is whether adequate power is available at the same time as a significant disturbance manifests itself.

Station-Keeping Buoy Model

For this example, we consider a generic buoy which generates power using a wind turbine, and maintains station with a water propulsion system. We simplify the problem using the following assumptions:

1) Drag in the water is dominated by a hydrophone cable with total area (A_d) of 0.47m^2 (assuming a diameter of 3/8" and a length of 50m). We use a drag coefficient of the cable (C_d) of 1.0.
2) Propulsion in the water is provided with an efficiency (η_p) of 0.5 (electrical through power delivered to the water). The propulsion system acts over an area A_p of 0.2 m^2.
3) Energy is provided by a wind turbine with efficiency (η_g) of 26% and area A_g equal to 1.0 m$^{2.}$ Efficiency is defined as conversion of wind to electrical power.

Using these parameters, we can derive the notional performance of the system. The forces acting on the buoy are thus the current drag of the cable, the reaction force on the wind turbine, and the force exerted by the propulsion system to keep the buoy on station. The drag force is:

$$\overrightarrow{F}_d = \frac{1}{2}\rho_o A_d c_d v_c^2 \widehat{v_c}$$

The reaction force for the wind generator is found by solving for the exit velocity of air from the wind turbine, v_{out} and using the change in air velocity to compute the force:

$$v_{out}^3 + v_{out}^2 v_w - v_{out} v_w^2 - v_w^3 + 2v_w^3 \eta_g = 0$$

$$\overrightarrow{F}_w = \frac{1}{2}\rho_{air} A_g \left(v_w^2 - v_{out}^2\right)\widehat{v_w}$$

Here $\widehat{v_c}$ and $\widehat{v_w}$ are the unit vectors in the direction of current and wind, respectively. The solution for v_{out} is not given here as it is lengthy and does not add materially to the discussion.

To maintain station, the propulsion unit must impart a change in velocity to the water (Δv). Assuming the change in velocity is much greater than the perturbing currents, the power required is related to the drag and reaction forces by:

$$P = \frac{\left|\overrightarrow{F_w} + \overrightarrow{F_d}\right|^{3/2}}{2\sqrt{\rho_o A_p}}$$

Using the parameters defined above, and the environmental data from M1, we compute the power needed for station keeping, and the power available from wind for a period when the currents are unusually high. This is shown in figure 5. Note that even in this situation the power available from even a modest wind turbine (η_g A_g P_{wind}) exceeds the power required to maintain station. Figure 6 shows a histogram of the difference of power available and power needed over the entire environmental record. This idealized station-keeping buoy has sufficient power to maintain position in more than 95% of the record.

Building on this Work

The example, simple though it may be, provides useful insights for system design. For example, the system encounters power deficits largely in periods in which both winds and currents are low. Thus it is important to understand the low wind characteristics of the buoy and its generating system. Commercial wind turbines have a minimum speed in which they operate, and even adding this simple improvement to the model will provide insight to the performance envelop of the system. Further, both electrical generation and propulsion systems have efficiencies that are a function of speed, and thus a more accurate model would reflect this speed-dependent efficiency. Also, a buoy which had significant drag characteristics higher in the water column would likely encounter much greater currents, and thus an examination of the consequences of the current profile is important. Finally, the disadvantage of some sailing strategies is also apparent, as situations involving sailing into the wind involve moving the boat back and forth at some angle to the wind, requiring the buoy to travel significantly faster through the water and therefore increasing the drag on the hydrophone cable.

With this example in mind, the trade study outline should be clear. In brief, we intend to:

1) Expand both the environmental description (insolation, wave characteristics, current profile when possible) and obtain data for other locations of interest.
2) Develop a portfolio of station-keeping buoy models including such factors as energy storage and modeling characteristics of subsystems important to buoy performance (e.g. motor performance as a function of speed).
3) Test the modeled buoys against the environmental data sets to understand performance.
4) Relate the model performance to test results from Monterey Bay POS tests.

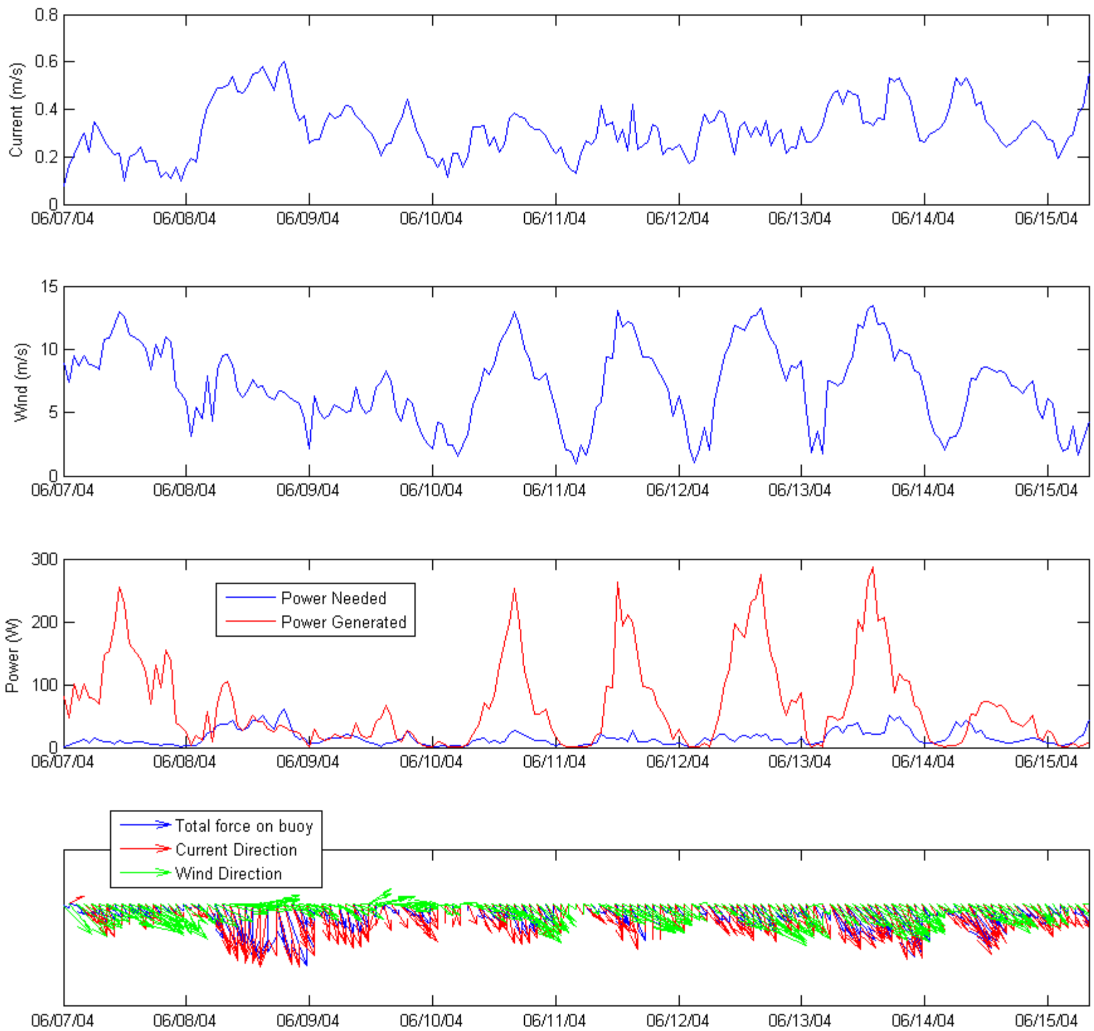

Figure 5: Performance of the simulated station-keeping buoy in a period with strong currents.

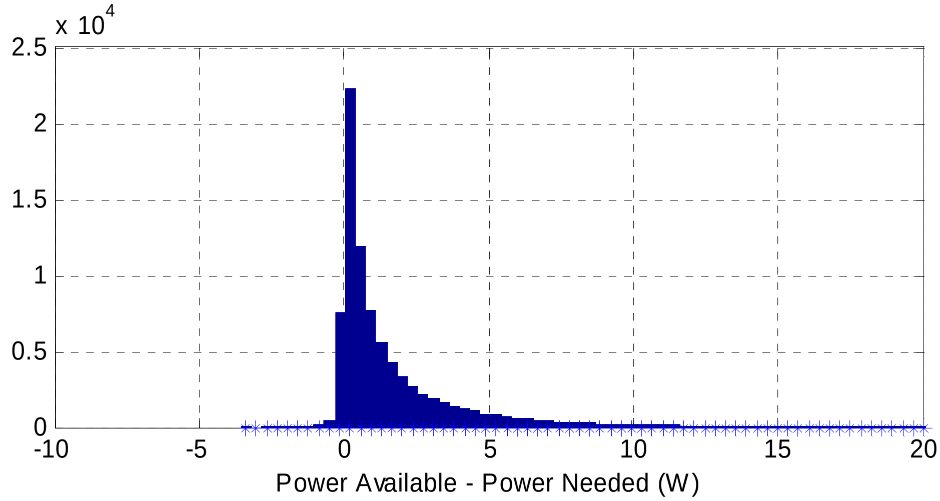

Figure 6: Histogram for entire environmental data set of occurrences of power.