I. INTRODUCTION

The preeminence of viscous dissipation over inertial effects at low Reynolds numbers leads to many interesting consequences for life and engineering efforts at the micron-scale. In particular, swimming at zero Reynolds number is impossible using time-reversible motions, a result known as the Scallop theorem [1]. As a result, at least two actuation degrees of freedom are necessary to generate locomotion. The breaking of this time-reversal symmetry has been studied both from a mathematical point of view, and in the context of modeling real organisms [2–6]. Unlike in high Reynolds number flows, such as those relevant in describing the swimming of fish and flying of birds, fluid motion at low Reynolds numbers is set almost instantaneously by the time-dependent geometries of the immersed bodies. Thus it is natural to inquire about the shapes of immersed (and possibly fluctuating) cell membranes, and their relationships to locomotion.

Membranes composed of lipid bilayers are ubiquitous in nature, and the study of bilayer vesicles as a model system for biological cells has yielded significant insight into their behavior [7, 8]. In addition to the biological relevance of lipid bilayer vesicles, or liposomes, advances in self-assembly have paved the way for other types of vesicles to be developed experimentally [9, 10]. Vesicles assembled from block copolymers [11], liquid crystal amphiphiles [12], and membranes with embedded proteins or anchored polymers [13–17] all have tunable material properties which can be manipulated with unprecedented control [18, 19]. It is also well known that many biological cells actively modify or maintain the shapes of their membranes [20, 21], either for developmental [22] or locomotive processes [23, 24].

Recently, synthetic microswimmers inspired by the locomotion of eukaryotic cells have been successfully designed in experiments [25], exploiting the planar beating of a flagellum-like organelle. Beyond biomimetic engineering, other small-scale synthetic swimmers or swimming strategies have also been proposed, both theoretically and experimentally [1, 6, 26–32]. One recently-studied example is a self-propelled colloidal particle which exploits asymmetrically-distributed chemical reactions to swim in a viscous fluid [33, 34].

In the same spirit, we consider theoretically in this paper a novel swimming mechanism based on prescribed shape transformations of a bilayer vesicle. By modulating only its volume and membrane composition, the vesicle can be made to change shape quasi-statically in thermal equilibrium. For two different theoretical vesicle models, we determine numerically the vesicle shapes through an enthalpy minimization, and the fluid-body interactions by solving a boundary integral formulation of the Stokes equations. When the control parameters are tuned appropriately to yield periodic but