Multi-Robot, Multi-Patch Foraging with Maximum Sustainable Yield

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Extended Abstract

Introduction

We introduce the Sustainable Robot Foraging (SuRF) problem, in which one or more robots must maximize the long-term profit obtained by harvesting resources from the environment. When the reward per unit harvested is constant or only slightly discounted over time this implies that the sources of resource must never be destroyed by over-harvesting, while under-harvesting fails to maximally exploit resources. This is a fundamental problem for living or artificial systems that aim to exploit biomass resources for long periods. The availability of resources over time is modeled using the classical logistic function originally proposed by Verhulst (1838) to model population growth, and since applied to the growth of tumors and many other natural systems. The logistic model improved on the earlier exponential growth model of Malthus (1798) by recognizing that populations generally can not grow unbounded, with growth limited as resources consumed by the existing population become scarce. A formula for obtaining the optimal harvest rate in systems with logistic growth was first described by Hjort et al. (1933) in their study of maximizing fish catches, and became well known in this context as the Maximum Sustainable Yield.

To apply these insights to the robotics context, we investigate a foraging problem in which autonomous robots must collect *pucks*; generic atomic objects of value to the robots' owner. Pucks are not distributed at random in the environment, but exist in areas of locally high density called *patches*. The number of pucks in a patch (the *patch size*) changes over time according to the logistic function, simulating a naturally regrowing resource that is harvestable in discrete units, such as mushrooms, acorns, fruits, animals and fish.

Once collected, pucks must be delivered to a central collecting point, at which time the robot system is credited with one unit of reward. Our goal is to maximize the total reward obtained by the system. If the reward per unit of resource is constant or discounted only slightly over time, then the optimal policy is to permanently sustain foraging while maximizing the instantaneous reward rate (Stephens et al., 2007; Wawerla and Vaughan, 2010). To achieve this, robots must harvest resources from each patch at the rate that provides the fastest resource growth rate at that patch. This implies that the patch will remain at some ideal population size. Collect pucks too slowly or too quickly and the patch is less than optimally productive. If a patch size gets below some lower bound, it can not regenerate and is permanently destroyed.

Figure 1: Robots forage for resources that demonstrate logistic population growth. To obtain maximum sustainable profit, the robots must harvest resources at the rate that maximizes the rate of regrowth. This is the Maximum Sustainable Yield. [Artwork © Christine Larson]

We used the Maximum Sustainable Yield formulation to find the optimal robot work allocations for our robot foraging problem. Realizing the model in a numerical simulation, we observe a well-known problem with MSY: the system is dynamically sensitive to small perturbations, so that the fixed allocation does not provide good sustainable foraging. To cope with this we devised a simple feedback controller that locally modulates the foraging rate at each patch to achieve sustainability and close to optimal performance. We demonstrated the controller achieving optimal foraging in a simple robot simulator.

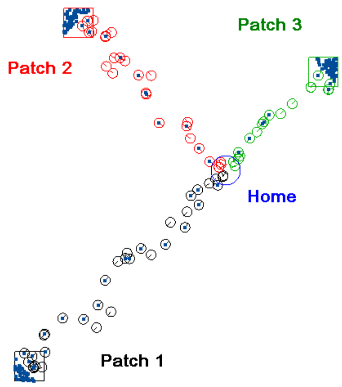


Figure 2: Screenshot from the Antix simulator. 80 robots (small circles) adaptively forage pucks (dark dots) from 3 patches (squares) and deliver them to the home (large circle).

Demonstration

We demonstrate a simple adaptive controller in the freely-available sensor-based robot simulator Antix[1]. Pucks are placed at random in the patches, the robot drives between home and goal using a simple kinematic controller, and detects pucks using an on-board sensor with limited range.

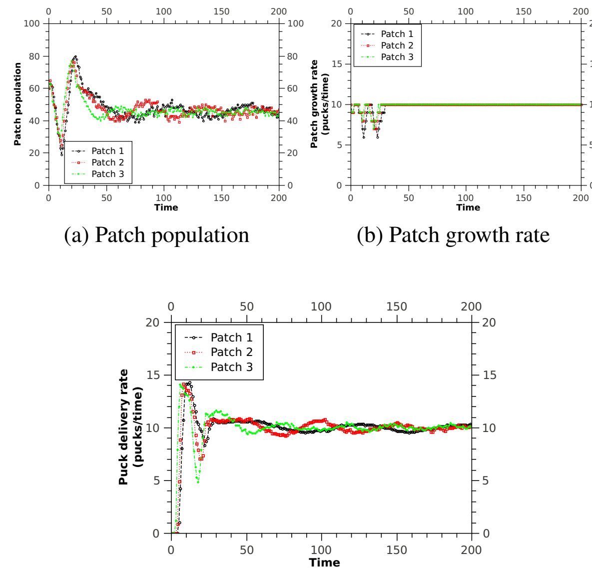
There are three patches, all with the same logistic growth parameters, but located at different distances from home, at 2, 3 and 4 times unit distance, as shown in Figure 2. The overall performance metric we mean to optimize is the sustained delivery rate of the entire robot system, which is simply the total number of pucks delivered by all robots per unit time. The optimal delivery rate is 10 pucks unit time.

Figure 3 shows an example system evolution for 100 robots. Patch population plot (a) shows the robots initially over-harvest all patches and the populations drop quickly. Adapting to the falling population, the robots increase their sleep time and the population climbs again, overshooting the ideal size until the robots adapt again, bringing the population back to the approximately optimal size. The patch growth rate is shown in (b), and the puck delivery rate is seen in (c), climbing from zero as robots are are deployed, rising above 10 pucks per unit time as the patch is over-harvested, dropping as the population declines, then converging close to the around the Maximal Sustainable Yield of 10 pucks per unit time for each patch. The excess work capacity has been turned into inactive robot "sleep" time to avoid over-harvesting.

Contributions

1. The introduction of the Sustainable Robot Foraging (SuRF) problem, and the first demonstration of sustainable robot foraging. This is the first work to examine optimal foraging strategies in robot systems where the robots' activity feeds back into the subsequent productivity of the environment;
2. The first application of Maximum Sustainable Yield model to robot foraging.

[1]http://github.com/rtv/Antix



(a) Patch population (b) Patch growth rate

(c) Puck delivery rate

Figure 3: Results: 100 robots adaptively foraging 3 patches of randomly placed pucks. Time units are hundreds of simulated seconds. Allocation is patch 1:=43 robots, 2:=33, 3:=24. Sustainable and optimal (maximum productivity is 10 pucks/unit time).

This is an early step towards the development of machines that can harvest biomass from the environment indefinitely without damaging it. This is a challenge that has defeated even the smartest primates, historically.

References

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