

Coordinating Heterogenous Agents for Fast Package Delivery — The Package Handoff Problem

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Abstract

How do you get a package from an initial location S to a destination point T using a fleet of “heterogenous” carrier agents (e.g. drones, taxis). By “heterogenous” we mean the two agents can have different capabilities like different maximum speed or different fuel capacity.

In the simplest version of the category of problems, we are given as input the initial locations of n agents in \mathbb{R}^2 each capable of a maximum speed $u_i > 0$ (where u_i need *not* be equal to v_j for $i \neq j$). Each agent can pick up the package and move to another point to *rendezvous with* and *hand off* the package to another agent. This other agent then either proceeds to T or decides to meet with and hand off the package to another agent, until the last agent decides to head directly to T .

The objective is to get the agents to cooperate to send the package from S to T in the least possible time. We call this the *Package Handoff Problem*.

To solve this problem and its various avatars we need to

1. Figure out which subset $S = \{i_1, i_2, \dots, i_k\}$ of the drones are used in the optimal schedule.
2. Find the order in which the handoffs happend between the drones used in a schedule.
3. Calculate the “handoff” points where drone i_m hands over the package to drone i_{m+1} , for $1 \leq m \leq k - 1$

This report is an algorithmic study of various heuristics developed to solve different variants of Package Handoff.

Contents

1	Single Package Handoff	2
1.1	Introduction	2
1.2	A note on source code	3
1.3	Problem: Unlimited Fuel, Different Drone Speeds	3
1.3.1	Handoff in a fixed order	5
1.3.2	Algorithm: One Dimensional Greedy Wavefront	6
2	Multiple Package Handoff	13
2.1	Problem: Drone Assignment To Packages	13
2.1.1	Algorithm: Repeated Bottleneck Matching	14
	Appendices	18
A	History and Previous Work	19
B	README.md	21
C	utils_graphics.py	22
D	utils_algo.py	23
E	Implementation of <code><Run Handlers></code>	25
F	Implementation of <code><Plotting></code>	32

Chapter 1

Single Package Handoff

1.1 Introduction

How do you get a package from an initial location S to a destination point T using a fleet of “heterogenous” carrier agents (e.g. drones, taxis). By “heterogenous” we mean the two agents can have different capabilities like different maximum speed or different fuel capacity.

In the simplest version of the category of problems, we are given as input the initial locations of n agents in \mathbb{R}^2 each capable of a maximum speed $u_i > 0$ (where u_i need not be equal to v_j for $i \neq j$). Each agent can pick up the package and move to another point to *rendezvous with* and *hand off* the package to another agent. This other agent then either proceeds to T or decides to meet with and hand off the package to another agent¹ and so on and so forth.

The objective is to get the agents to cooperate to send the package from S to T in the least possible time. We call this the *Package Handoff Problem*.

To solve this problem and its various avatars² we need to

1. Figure out which subset $S = \{i_1, i_2, \dots, i_k\}$ of the drones are used in the optimal schedule.
2. Find the order in which the handoffs happen between the drones used in a schedule.
3. Calculate the “handoff” points where drone i_m hands over the package to drone i_{m+1} ³

A real world instance of the basic Package Handoff problem, as described in the abstract, is when a ride hailing service must co-ordinate its fleet of taxis to transport a passenger from a given location in the quickest possible time to the target destination on the map. In this model, a passenger “hops rides” when two taxis meet: a taxi first gets to the passenger and takes him/her to a point where it rendezvous with another taxi, at which point the passenger swaps taxis. This process continues until the passenger hops onto a taxi that goes straight to the target.

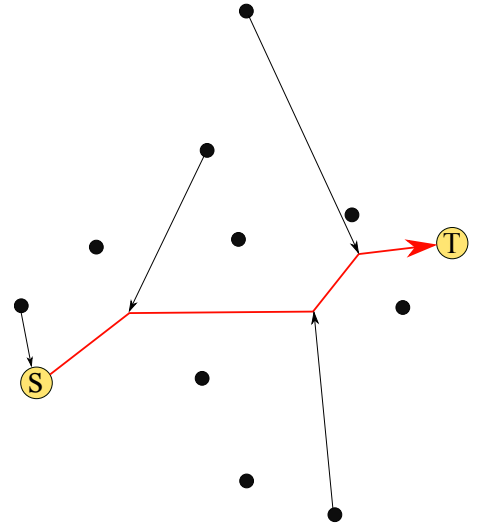


Figure 1.1: An instance of the Package Handoff problem for a single package being transported from S to T . Agents are located at the dots marked in black. The package travels along the red path. The agents all have different velocities, and in this example, assumed to have infinite battery capacity.

¹If it makes the package get to T faster

²Say when there are multiple packages to be delivered or a bound on fuel

³The last drone in the computed schedule, of course, flies directly to T

This package handoff process is depicted in [Figure 1.1](#).

1.2 A note on source code

Many of the heuristics algorithms described here are implemented as literate programs [6] in Python 2.7.12 using the NuWeb tool [2] available from <http://nuweb.sourceforge.net/> alongside associated theoretical and empirical analysis. All the algorithmic code goes into the file `pholib.py`, and any associated helper codes go into the files which are named as `utils_*.py`. The code for these utility files has been given in the appendices.

The `pholib.py` file looks like

"src/pholib.py" 3≡

```
from colorama import Fore, Style
from matplotlib import rc
import matplotlib as mpl
import matplotlib.pyplot as plt
from scipy.optimize import minimize
from sklearn.cluster import KMeans
import numpy as np
import argparse, inspect, itertools, logging
import os, time, sys
import pprint as pp, randomcolor
import utils_algo, utils_graphics
```

⟨ *Algorithms* 6, ... ⟩

⟨ *Run Handlers* 23 ⟩

⟨ *Plotting* 30 ⟩

◇

The chapters are devoted to fleshing out the chunks ⟨*Algorithms*⟩ and ⟨*Experiments*⟩. The ⟨*Run Handlers*⟩ and ⟨*Plotting*⟩ chunks is mainly to deal with interactive matplotlib input, and as such are boring and banished to the Appendix ☹.

All source code files are tangled to the `src` directory. The point of entry for the code are `main*.py` which are implemented separately in the `src` directory, since their contents can change based on what library code is being called for during development and testing. Since these files are very short and the mechanics clear, they are implemented as standalone files (i.e. not inside this document) but directly in the `src` folder itself. To run the code in interactive mode run the code as `python src/main_interactive.py` on a Unix / Windows terminal in the root folder of the project ⁴.

For a short overview of previous work on this problem see Appendix.

The `README` file containing instructions for running the source code and experiments is listed in the appendix (also available on the Github repository)

Each of the following sections correspond to a fixed variant of the package handoff problem and describe algorithms for that specific variant. Enough talk! Onto algorithms!

1.3 Problem: Unlimited Fuel, Different Drone Speeds

Much of the machinery developed in solving this basic basic basic question will be generalized and extended to other variants of the package handoff problem.

⁴This code has been tested on an 64 bit machine running Linux Mint 18.3 (Sylvia) running the Linux Kernel version 4.10.0-38-generic with an Intel(R) Core(TM) i7 CPU 960 @ 3.20GHz CPU

We repeat the problem definition and fix some notation that will be used for the remainder of the section

We are given as input the initial locations P_i of n agents in \mathbb{R}^2 each capable of a maximum speed $u_i > 0$ (where u_i need not be equal to u_j for $i \neq j$). Each agent can pick up the package and move to another point to rendezvous with and hand off the package to another agent. This other agent then either proceeds to T or decides to meet with and hand off the package to another agent and so on. The objective is to get the agents to cooperate to send the package from S to T in the least possible time.

We represent the handoff points as follows $H_{i_1} \dots H_{i_k}$ for $0 \leq i_0, \dots, i_k \leq n$ stand for points where the drones with labels i_0, \dots, i_k hand the package off in that order. More precisely H_{i_j} is the point where drone i_{j-1} hands off the package to drone i_j for $1 \leq j \leq k$.

A solution to the package handoff problem is completely specified by computing the handoff points *and* the drone ids involved in the exchange at each handoff point.

The optimal schedule is denoted OPT . It is easy to see the statements of the following structural lemma always hold for OPT .

Lemma 1. *In OPT*

- A.** *A package is always transferred to a faster drone at a handoff point.*
- B.** *A drone handles a package at most once i.e. if a drone hands off the package, it will never be involved in a handling that package again.*
- C.** *All drones involved in the handoff start moving simultaneously at time $t = 0$*
- D.** *No two drones wait at a rendezvous point before rendezvous happens.* ^a
- E.** *The path of the package is a radially monotone piecewise straight polygonal curve with respect to the direction ST no matter what the initial positions P_i or speeds u_i of the drones.*
- F.** *$\frac{|ST|}{v_{max}}$ is a (trivial) lower bound for OPT , where v_{max} denotes the speed of the fastest drone.*

^awaiting can happen in other problem variants say when there is limited fuel or only a finite set of allowed rendezvous points

Proof. **TODO!**

□

1.3.1 Handoff in a fixed order

If we know the drones involved in the handoff *along with* the order of handoff then we can compute the handoff points — and hence the path of the package — exactly via convex optimization as outlined in Lemma 2. This fact will be exploited in many heuristics: such methods will compute a subset of drones involved in the handoff (alongwith the handoff order) followed by a call to the convex program.

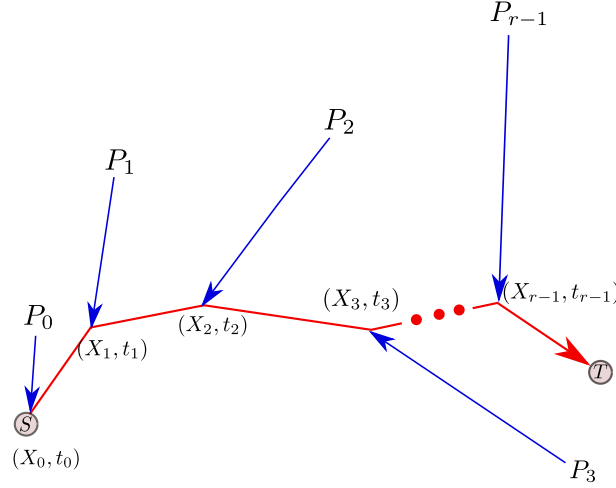


Figure 1.2: The path of the package is shown in red. The drones involved in the handoff are labelled P_i in the prespecified handoff order.

Lemma 2. Given as input are drones with initial positions $P_i \in \mathbb{R}^2$, with speeds $u_i > 0$ for $1 \leq i \leq r-1$, the initial position S and final destination T for the package.^a The drones are expected to transport the package by handing of the package in the order $1, 2, \dots, r$. Let t_i denote the departure time on a global clock from the i 'th handoff point X_i .

Then the minimum time and handoff points for transporting the package and the handoff points can be calculated by the following convex program

$$\min_{t_i, X_i} \quad t_{r-1} + \frac{\|T - X_{r-1}\|}{u_{r-1}}$$

subject to the constraints

$$\begin{aligned} X_0 &= S \\ t_i &\geq \frac{\|P_i - X_i\|}{u_i} & 0 \leq i \leq r-1 \\ t_i + \frac{\|X_{i+1} - X_i\|}{u_i} &\leq t_{i+1} & 0 \leq i \leq r-2 \end{aligned}$$

^aSee Figure 1.3.1 for an illustration of the notation used in this lemma

Proof. **TODO!**

□

The following function is just an implentation of the convex program just described. Here **drone_info** is a list of tuples, where each tuple consits of the initial position and speed of the drone. The order of the drones is assumed to be that in which the list of drones is provided. **source** and **target** are just coordinate locations of S and T respectively. We use the CVXPY [3] library as a black-box convex optimization solver.

(Algorithms 6) \equiv

```
def algo_pho_exact_given_order_of_drones ( drone_info, source, target ):
    import cvxpy as cp

    source = np.asarray(source)
    target = np.asarray(target)

    r = len(drone_info)
    source = np.asarray(source)
    target = np.asarray(target)

    # Variables for rendezvous points of drone with package
    X, t = [], []
    for i in range(r):
        X.append(cp.Variable(2)) # vector variable
        t.append(cp.Variable( )) # scalar variable

    # Constraints
    constraints_S = [ X[0] == source ]

    constraints_I = []
    for i in range(r):
        constraints_I.append(0.0 <= t[i])
        constraints_I.append(t[i] >= cp.norm(np.asarray(drone_info[i][0])-X[i])/drone_info[i][1])

    constraints_L = []
    for i in range(r-1):
        constraints_L.append(t[i] + cp.norm(X[i+1] - X[i])/drone_info[i][1] <= t[i+1])

    objective = cp.Minimize(t[r-1]+cp.norm(target-X[r-1])/drone_info[r-1][1])

    prob = cp.Problem(objective, constraints_S + constraints_I + constraints_L)
    print Fore.CYAN
    prob.solve(solver=cp.SCS,verbose=True)
    print Style.RESET_ALL

    package_trail = [ np.asarray(X[i].value) for i in range(r) ] + [ target ]
    return package_trail
```

◇

Fragment defined by 6, 9ab, 10, 14a.

Fragment referenced in 3.

We next describe a heuristic that use Continuous Dijkstra [11] type approach in computing approximate solutions to *OPT*.

1.3.2 Algorithm: One Dimensional Greedy Wavefront

In this heuristic we first constrain the package to travel along the line \vec{ST} , then compute the subset of the drones involved in the schedule, and finally pass of the list of drones involved to the convex program given in Lemma 2 to calculate the rendezvous points.

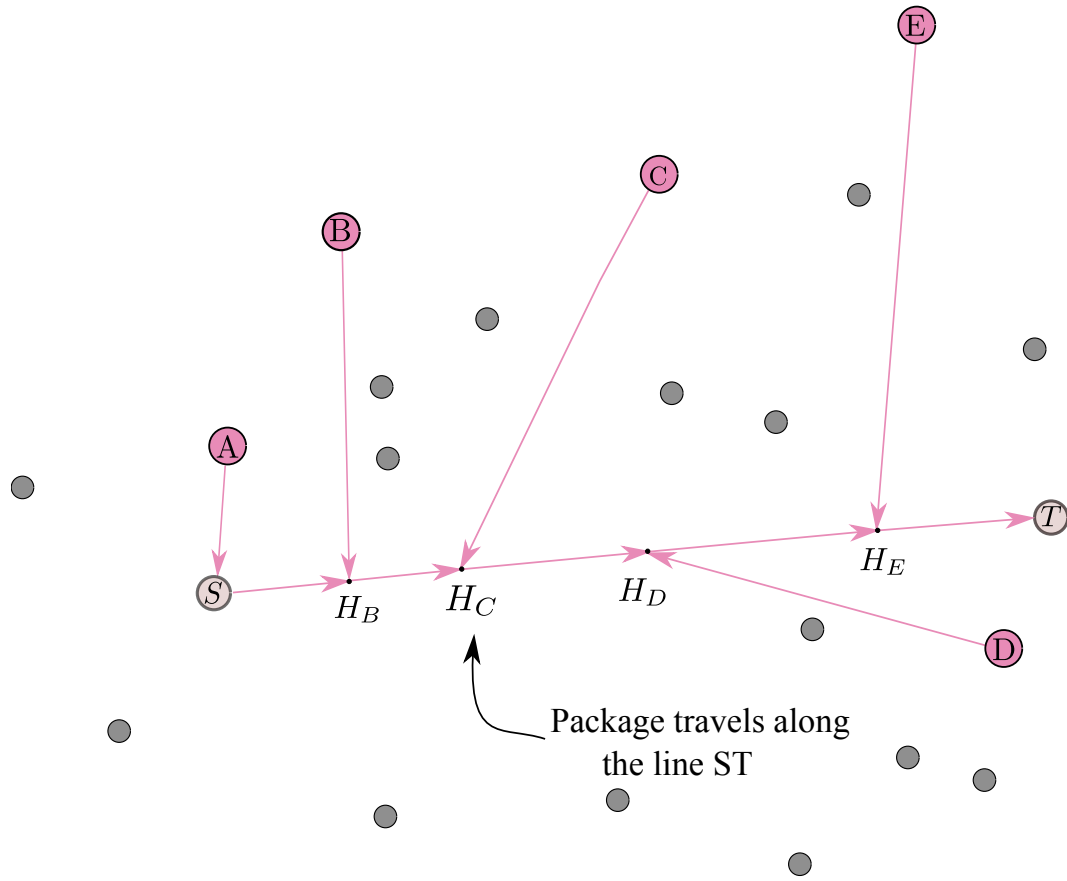


Figure 1.3: The package travels along the straight line \vec{ST} . The point where drone A hands off the package to drone B depicted as H_B , and similarly for other drones. Drones involved in the handoff are marked in pink. Those not involved are marked in gray. Two drones may have different speed.

Algorithm 1: ONE DIMENSIONAL GREEDY WAVEFRONT

Input:

1. Coordinates of initial position of source S and target T of the package.
2. Coordinates of the onital positions P_i of each drone $1 \leq i \leq n$.
3. Maximum possible speed u_i of each drone $1 \leq i \leq n$.

Output:

1. t^* : The time required for the package to get from S to T .
2. $L = (i_1, i_2, \dots, i_k)$: An ordered list of indices of the drones involved in the handoff.
3. $\mathcal{H} = \{S\} \cup \{H_{i_j} \mid j \geq 2\}$: An ordered list of handoff points. $H_{i_j} \in \mathbb{R}^2$ is where the drone with index i_j picks up the package from drone i_{j-1} .

```

1  $t \leftarrow 0$  // Time on the global clock
2  $wavelets \leftarrow [(i, 0) \mid 0 \leq i \leq n]$  // Active Wavelets: indices and current radius

/* Find first wavelet to reach  $S$  and update  $wavelets$  */
/* Start wavelet expansion from  $S$  */
3 for  $i \leftarrow 1$  to  $r$  do
4   while  $n \geq c_i$  do
5      $C \leftarrow C \cup \{c_i\}$ 
6      $n \leftarrow n - c_i$ 
7   end
8 end
9 return  $t^*, L, \mathcal{H}$ 

```

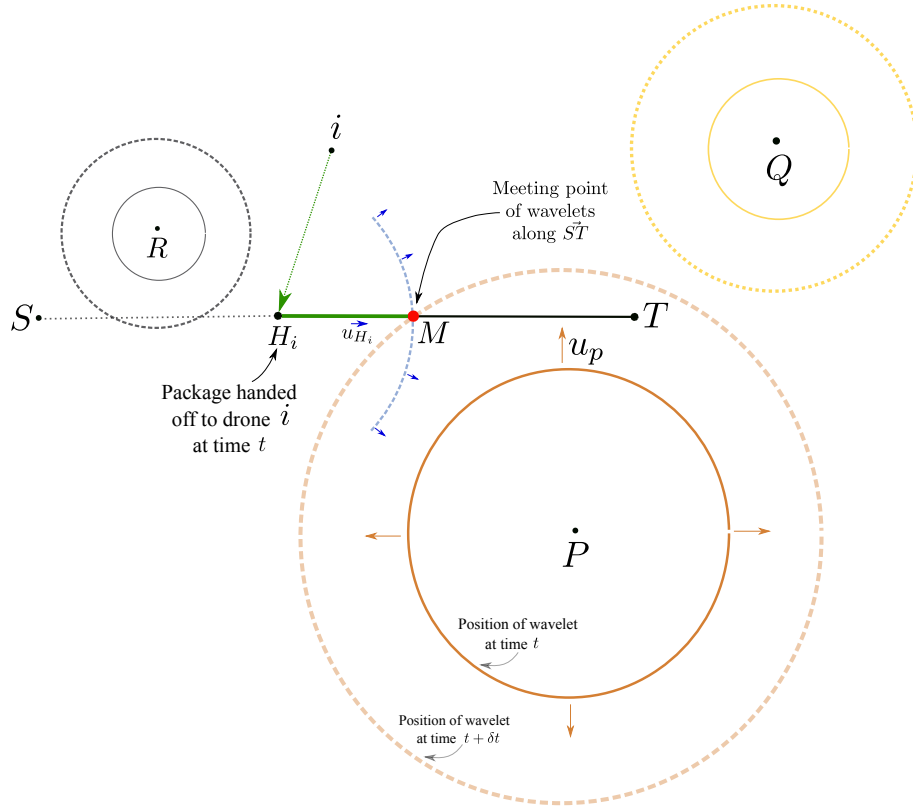


Figure 1.4: Intersection of two expanding wavelets along $H_i T$. The figure shows snapshots of two times; one at time t when the package has just been handed off to drone i at H_i and another at time $t + \delta t$ when a wavelet corresponding a drone faster than drone i meets the wavelet expanding from H_i with speed u_i at M

⟨ Algorithms 9a ⟩ ≡

```
def makespan(drone_info, used_drones, package_trail):

    assert len(package_trail) == len(used_drones)+1, ""
    makespan = 0.0
    counter = 0
    for idx in used_drones:
        dronespeed = drone_info[idx][1]

        makespan += time_of_travel(package_trail[counter],\
                                   package_trail[counter+1],
                                   dronespeed)

        counter += 1

    return makespan

def time_of_travel(start, stop, speed):
    start = np.asarray(start)
    stop = np.asarray(stop)
    return np.linalg.norm(stop-start)/speed
```

◇

Fragment defined by 6, 9ab, 10, 14a.

Fragment referenced in 3.

Defines: makespan, Never used, time_of_travel 10.

⟨ Algorithms 9b ⟩ ≡

```
def get_interception_time(s, us, p, up, t, t0) :

    t_m = t - s # the _m subscript stands for modify
    t_m = t_m / np.linalg.norm(t_m) # normalize to unit

    # For rotating a vector clockwise by theta,
    # to get the vector t_m into alignment with (1,0)
    costh = t_m[0]/np.sqrt(t_m[0]**2 + t_m[1]**2)
    sinth = t_m[1]/np.sqrt(t_m[0]**2 + t_m[1]**2)

    rotmat = np.asarray([[costh, sinth],
                          [-sinth, costh]])

    assert np.linalg.norm((rotmat.dot(t_m) - np.asarray([1,0]))) <= 1e-6,\
           "Rotation matrix did not work properly. t_m should get rotated\
           onto [1,0] after this transformation"

    p_shift = p - s
    p_rot = rotmat.dot(p_shift)
    [alpha, beta] = p_rot

    # Solve quadratic documented in the snippets above
    roots = np.roots([ (1.0/us**2 - 1.0/up**2),
                       2*t0/us + 2*alpha/up**2 ,
                       t0**2 - alpha**2/up**2 - beta**2/up**2])
```

```

## The quadratic should always a root.
groots = np.real(groots) # in case the imaginary parts
groots.sort()           # of the roots are really small

x = None
for root in groots:
    if root > 0.0:
        x = root
        break
assert abs(x/us+t0 - np.sqrt((x-alpha)**2 + beta**2)/up) <= 1e-6 , \
    "Quadratic not solved perfectly"

tI = x/us + t0
return tI

```

◇

Fragment defined by 6, 9ab, 10, 14a.

Fragment referenced in 3.

Defines: `get_interception_time` 10.

⟨ *Algorithms* 10 ⟩ ≡

```

def extract_coordinates(points):

    xs, ys = [], []
    for pt in points:
        xs.append(pt[0])
        ys.append(pt[1])
    return np.asarray(xs), np.asarray(ys)

def algo_odw(drone_info, source, target,
             plot_tour_p = False):

    from scipy.optimize import minimize

    source = np.asarray(source)
    target = np.asarray(target)
    # unit vector pointing from source to target
    sthat = (target-source)/np.linalg.norm(target-source)

    numdrones = len(drone_info)
    clock_time = 0.0

    # Find the drone which can get to the source the quickest
    tmin = np.inf
    imin = None
    for idx in range(numdrones):
        initdroneposn = drone_info[idx][0]
        dronespeed = drone_info[idx][1]
        tmin_idx = time_of_travel(initdroneposn, source, dronespeed)

        if tmin_idx < tmin:
            tmin = tmin_idx
            imin = idx

    clock_time = tmin

    current_package_handler_idx = imin

```

```

current_package_position    = source

drone_pool = range(numdrones)
drone_pool.remove(imin)
used_drones = [imin]

package_trail_straight = [current_package_position]

package_reached_p    = False
while not(package_reached_p):

    time_to_target_without_help = \
        np.linalg.norm((target-current_package_position))/ \
        drone_info[current_package_handler_idx][1]

    tI_min    = np.inf
    idx_tI_min = None
    for idx in drone_pool:

        us = drone_info[current_package_handler_idx][1]
        up = drone_info[idx][1]

        if up <= us: # slower drones are useless, so skip rest of the iteration
            continue
        else:
            s = current_package_position
            p = np.asarray(drone_info[idx][0])

            tI = get_interception_time(s, us, p, up, target, clock_time)

            if tI < tI_min:
                tI_min    = tI
                idx_tI_min = idx

    if time_to_target_without_help < tI_min :
        package_reached_p = True
        package_trail_straight.append(target)

    else:
        package_handler_speed    = \
            drone_info[current_package_handler_idx][1]
        current_package_position = \
            current_package_position + \
            package_handler_speed * (tI_min - clock_time) * sthat
        package_trail_straight.append(current_package_position)

        clock_time    = tI_min
        current_package_handler_idx = idx_tI_min

        drone_pool.remove(idx_tI_min)
        used_drones.append(idx_tI_min)

package_trail_cvx = \
    algo_pho_exact_given_order_of_drones(\
        [drone_info[idx] for idx in used_drones],source,target)
mspan_straight = makespan(drone_info, used_drones, package_trail_straight)
mspan_cvx      = makespan(drone_info, used_drones, package_trail_cvx)

if plot_tour_p:

```

```

fig0, ax0 = plt.subplots()
plot_tour(fig0, ax0, "ODW: Straight Line", source, target, \
          drone_info, used_drones, package_trail_straight)

fig1, ax1 = plt.subplots()
plot_tour(fig1, ax1, "ODW: Straight Line, Post Convex Optimization", source, target, \
          drone_info, used_drones, package_trail_cvx)
plt.show()

```

```

return used_drones, package_trail_straight, mspan_straight, package_trail_cvx, mspan_cvx

```

◇

Fragment defined by 6, 9ab, 10, 14a.

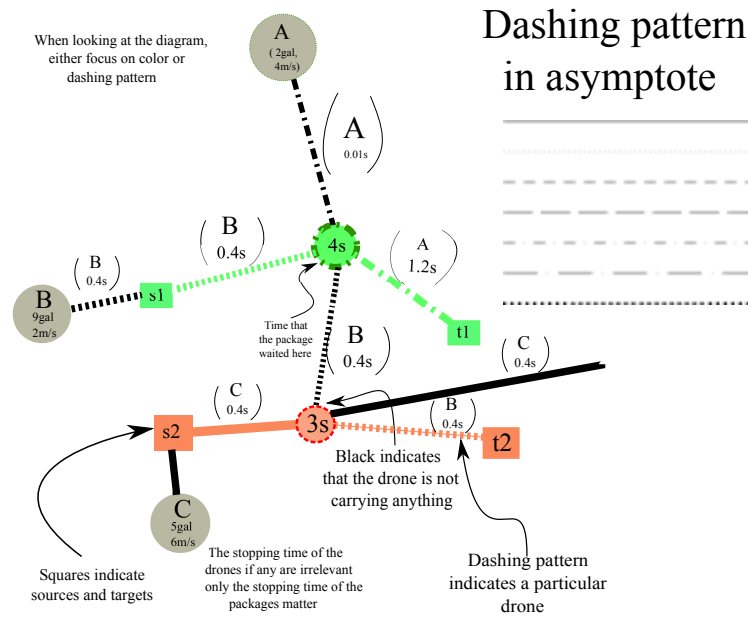
Fragment referenced in 3.

Defines: algo_odw 23, extract_coordinates, Never used.

Uses: get_interception_time 9b, time_of_travel 9a.

Chapter 2

Multiple Package Handoff



What's more fun than delivering a single package? Delivering multiple packages! The moment, we generalize from a single to multiple packages the problem becomes enormously more interesting along with several possible generalizations to the statement of the problem. Each section is dedicated to one such generalization along with a description of algorithms and heuristics to solve them.

2.1 Problem: Drone Assignment To Packages

We are given as input the initial locations P_i of n agents in \mathbb{R}^2 each capable of a maximum speed $u_i > 0$. Also given are $k \leq n$ source target pairs S_j, T_j where S_j for $j \leq k$ denotes the beginning position of a package that has to get to target point T_j .

Each agent is allowed to be involved in the transport of at most one package. More than one agent is allowed to be assigned to a package. Agents assigned to a package can coordinate to rendezvous and relay the package from its source to its destination (exactly as in the single package handoff case)

The objective is to perform an assignment of agents to the packages so that the time taken to deliver the last package to its target is minimized, i.e. the makespan of the deliveries of the packages from sources to their destinations is minimized.

2.1.1 Algorithm: Repeated Bottleneck Matching

The approach taken here is again based on Continuous Dijkstra. At the start of the algorithm, we assume each of the packages are constrained to travel along the straight line segment joining its source and target. We then imagine wavelets expanding at speed u_i from each of the drone positions and perform an incremental assignment of the drones to the packages as the wavelet expansion proceeds. The assignment is done via bottleneck matching in an appropriately constructed bipartite graph. The matching algorithm is run everytime a certain “event” is detected.

Once the final assignment of drones to packages has been performed, we run the convex optimization solver described in [subsection 1.3.1](#) to get the exact trajectory for each of the packages for the given assignment.

The rest of this section is devoted to making the above description more precise alongside the implementation for `algo_repbob`. Here is the main outline of the implementation.

Algorithm 14a \equiv

```
import networkx as nx

def algo_repbob(drone_info, sources, targets, plot_tour_p = False):

    Sanity checks on input for algo_repbob 14b
    Basic setup 15

    package_delivered_p = [ False for _ in range(numpackages) ]
    current_package_handler = [ None for _ in range(numpackages) ]
    current_package_position = sources
    current_package_speed = [ 0.0 for _ in range(numpackages) ]
    drone_wavelet_info = [{ 'wavelet_center': posn, 'radius': 0.0 }
                          for posn in drone_initposns]
    drone_pool = range(numdrones)

    while not all(package_delivered_p):
        Detect event type ?
        Process event ?
        Update drone pool ?

    ◇
```

Fragment defined by [6](#), [9ab](#), [10](#), [14a](#).

Fragment referenced in [3](#).

Defines: `algo_repbob` [23](#).

To start things off, we enforce the constraint that the number of drones should be greater than the number of packages. Also the number of packages is equal to the number of sources which in turn is equal to the number of targets. These conditions are encoded as sanity checks in the code chunk below that is incorporated at the beginning of the function

Sanity checks on input for algo_repbob 14b \equiv

```
assert len(drone_info) >= len(sources), \
    "Num drones should be >= the num source-target pairs"

assert len(sources) == len(targets), \
    "Num sources should be == Num targets"

◇
```

Fragment referenced in [14a](#).

The lists `sources`, `targets`, `drone_initposns` and `drone_speeds` are all *constant* throughout the execution of the algorithm. They denote the list of sources, targets, initial position and speeds of the drones respectively. For package `i`, its source and destination are respectively `source[i]` and `target[i]`.

⟨ Basic setup 15 ⟩ ≡

```
sources    = [np.asarray(source) for source in sources]
targets    = [np.asarray(target) for target in targets]

drone_initposns = [ np.asarray(initposn) for (initposn, _) in drone_info ]
drone_speeds    = [ speed                for (_,    speed) in drone_info ]

numpackages = len(sources)
numdrones   = len(drone_info)
◇
```

Fragment referenced in 14a.

Then, we create some lists that keep track of various states in the main **while** loop of the algorithm.

package_delivered_p is a Boolean list where the i^{th} element keeps track whether the package with id i has been delivered to its destination. The main **while** loop stops when all flags are set to **True**.

current_package_handler is a list of integer indices where the i^{th} element indicates the id of the drone currently carrying the package along the straight line segment $S_i T_i$ enroute to T_i .

current_package_position is a list of (x, y) coordinates where the i^{th} element indicates the coordinates of the drone with id `current_package_handler[i]`.

current_package_speed is a list keeping track of the current speed with which the package is moving. More precisely, the i^{th} element is the speed of the currently handling the i^{th} package. Since the packages are initially not being handled by any of the drones, all package speeds are initialized to 0.0.

drone_wavelet_info is a list of dictionaries, one dictionary per drone. Each such dictionary keeps track of information about a wavelet corresponding to every drone viz. the center of the wavelet about which the expansion is happening (by the **wavelet_center** attribute), and the current radius of the wavelet (by the **radius** attribute).

drone_pool is a list of ids of drones that can be considered for the bottleneck matching process for the next iteration of the **while** loop. In each iteration the size of this list goes down by exactly one.

Each iteration corresponds to processing exactly one event. There are exactly two types of (mutually exclusive) events in this algorithm.

Type I: A package gets delivered to its assigned destination

Type II: A wavelet corresponding to a drone (not handling a package) meets up with a drone currently handling a package.

In both event types, a drone gets taken out of the drone pool: for the Type I event the drone that just delivered the package to the destination; for the Type II event the drone that just handed off the package.

2.1.1.1 Step: Detecting Event Type

2.1.1.2 Step: Process Event

2.1.1.3 Step: Update Drone Pool

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Appendices

Appendix A

History and Previous Work

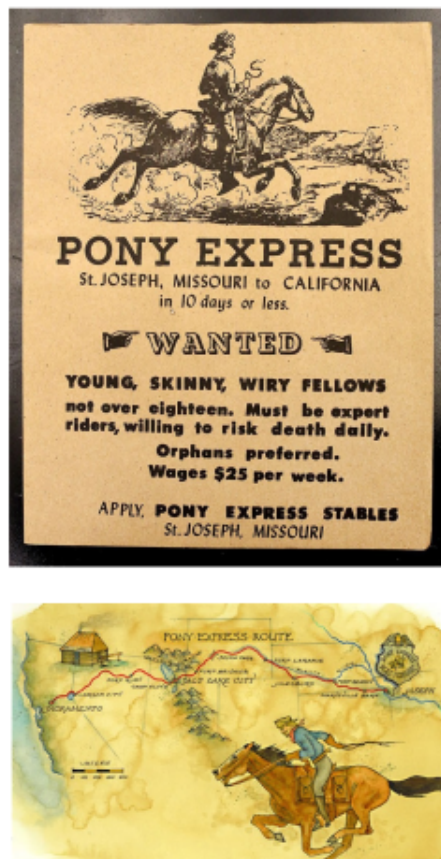


Figure A.1: A job application poster and a relay route used for the Pony Express. Images taken from [16] and [14] respectively.

A system of using relays for delivering packages is not a particularly new idea. A famous (and shortlived!) example of such a relay system was the Pony Express company which was used a system of a relay of horse riders to transport mail from St. Joseph, Missouri to Sacramento, California.

To quote the Wikipedia article

“Operated by Central Overland California and Pike’s Peak Express Company, the Pony Express was a great financial investment to the U.S. During its 18 months of operation, it reduced the time for messages to travel between the Atlantic and Pacific coasts to about 10 days. It became the West’s most direct means of east-west communication before the transcontinental telegraph was established (October 24, 1861), and was vital for tying the new U.S. state of California with the rest of the United States. The Pony Express demonstrated that a unified transcontinental system of communications could be established and operated year-round.”

While the invention of the telegraph might have run the Pony Express out of business, the idea of using relay agents such as drones — instead of horses! — to transfer packages can have applications today for sending physical goods (which of course can’t be telegraphed! ☺) such as life-saving medicines in under-developed countries or in disaster relief areas. ZipLine[15] [5] and Matternet [10] are just two of the companies which are involved in building networks of drones for precisely such missions.



Figure A.2: Dabbawallas exchanging lunchboxes (dabbas) at a relay point. Image from [9]

Another relay system for package deliveries (135 years old and still functioning!) is that of the *dabbawallas*¹ used for transporting lunch boxes from homes and restaurants to

people at work in Mumbai, India. To quote from [12]

Four thousand five hundred semi-literate dabbawalas collect and deliver 175,000 packages within hours. What should we learn from this unique, simple and highly efficient 120-year-old logistics system? [...] After the customer leaves for work, her lunch is packed into a tiffin provided by the dabbawala. A color-coded notation on the handle identifies its owner and destination. Once the dabbawala has picked up the tiffin, he moves fast using a combination of bicycles, trains and his two feet.

A BBC crew filming dabbawalas in action was amazed at their speed. “Following our dabbawala wasn’t easy, our film crew quickly lost him in the congestion of the train station. At Victoria Terminus we found other fast moving dabbawalas, but not our subject... and at Mr Bhapat’s ayurvedic pharmacy, the lunch had arrived long before the film crew,” the documentary noted wryly. So, how do they work so efficiently?

The entire system depends on teamwork and meticulous timing. Tiffins are collected from homes between 7.00 am and 9.00 am, and taken to the nearest railway station. At various intermediary stations, they are hauled onto platforms and sorted out for area-wise distribution, so that a single tiffin could change hands three to four times in the course of its daily journey.

At Mumbai’s downtown stations, the last link in the chain, a final relay of dabbawalas fan out to the tiffins’ destined bellies. Lunch hour over, the whole process moves into reverse and the tiffins return to suburban homes by 6.00 pm.

See <https://youtu.be/dX-0e12wuEU> for a short video on the dabbawallas.

¹literally: lunchbox carriers

Appendix B

README.md

This README file can be read more clearly alongside its appropriate formatting at https://github.com/gtelang/PackageHandoff_Python/tree/master/packagehandoff_lit

"README.md" 19≡

To run this code, you will need a distribution of Python 2.7.12 along with the following libraries

- networkx
- matplotlib
- numpy
- scipy
- cgal-bindings
- cvxpy

All source code is contained in the .web file. If you modify the file, the resulting code and corresponding description file can be weaved and tangled with the script 'weave-tangle.sh'. You will need the

- [pdflatex](https://linux.die.net/man/1/pdflatex)
- [nuweb](http://nuweb.sourceforge.net/)
- [asymptote](http://asymptote.sourceforge.net/)

executables to be somewhere on your system's path.

All source code is in the 'src' directory. The asy2d, asy3d and docs folders can be neglected since they contain images and documents referenced in the 'packagehandoff.pdf' file. From the point of view of `_running_` the code they can be ignored.

◇

Appendix C

utils_graphics.py

This file contains useful functions for visualization and plotting functions described in the previous chapters.

"src/utils_graphics.py" 20≡

```
from matplotlib import rc
from colorama import Fore
from colorama import Style
from scipy.optimize import minimize
from sklearn.cluster import KMeans
import argparse
import itertools
import math
import matplotlib as mpl
import matplotlib.pyplot as plt
import numpy as np
import os
import pprint as pp
import randomcolor
import sys
import time

xlim, ylim = [0,1], [0,1]

# Borrowed from https://stackoverflow.com/a/9701141
import numpy as np
import colorsys

def get_colors(num_colors, lightness=0.2):
    colors=[]
    for i in np.arange(60., 360., 300. / num_colors):
        hue      = i/360.0
        saturation = 0.95
        colors.append(colorsys.hls_to_rgb(hue, lightness, saturation))
    return colors
◇
```


Appendix D

utils_algo.py

This file contains useful functions for writing algorithms described in the previous chapters.

"src/utils_algo.py" 21≡

```
import numpy as np
import random
from colorama import Fore
from colorama import Style

def vector_chain_from_point_list(pts):
    vec_chain = []
    for pair in zip(pts, pts[1:]):
        tail= np.array (pair[0])
        head= np.array (pair[1])
        vec_chain.append(head-tail)

    return vec_chain

def length_polygonal_chain(pts):
    vec_chain = vector_chain_from_point_list(pts)

    acc = 0
    for vec in vec_chain:
        acc = acc + np.linalg.norm(vec)
    return acc

def pointify_vector (x):
    if len(x) % 2 == 0:
        pts = []
        for i in range(len(x))[:2]:
            pts.append( [x[i],x[i+1]] )
        return pts
    else :
        sys.exit('List of items does not have an even length to be able to be pointified')

def flatten_list_of_lists(l):
    return [item for sublist in l for item in sublist]

def print_list(xs):
    for x in xs:
        print x

def partial_sums( xs ):
    psum = 0
    acc = []
    for x in xs:
```

```

        psum = psum+x
        acc.append( psum )
    return acc
def are_site_orderings_equal(sites1, sites2):

    for (x1,y1), (x2,y2) in zip(sites1, sites2):
        if (x1-x2)**2 + (y1-y2)**2 > 1e-8:
            return False
    return True
def bunch_of_non_uniform_random_points(numpts):
    cluster_size = int(np.sqrt(numpts))
    numcenters = cluster_size

    import scipy
    import random
    centers = scipy.rand(numcenters,2).tolist()

    scale, points = 4.0, []
    for c in centers:
        cx, cy = c[0], c[1]
        # For current center $c$ of this loop, generate \verb|cluster_size| points uniformly in a square centered a

        sq_size = min(cx,1-cx,cy, 1-cy)
        loc_pts_x = np.random.uniform(low=cx-sq_size/scale, high=cx+sq_size/scale, size=(cluster_size,))
        loc_pts_y = np.random.uniform(low=cy-sq_size/scale, high=cy+sq_size/scale, size=(cluster_size,))
        points.extend(zip(loc_pts_x, loc_pts_y))

    # Whatever number of points are left to be generated, generate them uniformly inside the unit-square

    num_remaining_pts = numpts - cluster_size * numcenters
    remaining_pts = scipy.rand(num_remaining_pts, 2).tolist()
    points.extend(remaining_pts)

    return points

def write_to_yaml_file(data, dir_name, file_name):
    import yaml
    with open(dir_name + '/' + file_name, 'w') as outfile:
        yaml.dump( data, outfile, default_flow_style = False)

```

◇

Appendix E

Implementation of **⟨Run Handlers⟩**

This chunk contains code required for the interactive input of sites and agents onto the canvas.

⟨*Run Handlers 23*⟩ ≡

```
# Set up logging information relevant to this module
logger=logging.getLogger(__name__)
logging.basicConfig(level=logging.DEBUG)

def debug(msg):
    frame,filename,line_number,function_name,lines,index=inspect.getouterframes(
        inspect.currentframe())[1]
    line=lines[0]
    indentation_level=line.find(line.lstrip())
    logger.debug('{i} [{m}]'.format(
        i='.'*indentation_level, m=msg))

def info(msg):
    frame,filename,line_number,function_name,lines,index=inspect.getouterframes(
        inspect.currentframe())[1]
    line=lines[0]
    indentation_level=line.find(line.lstrip())
    logger.info('{i} [{m}]'.format(
        i='.'*indentation_level, m=msg))

xlim, ylim = [0,1], [0,1]

def applyAxCorrection(ax):
    ax.set_xlim([xlim[0], xlim[1]])
    ax.set_ylim([ylim[0], ylim[1]])
    ax.set_aspect(1.0)

def clearPatches(ax):
    # Get indices coresponding to the polygon patches
    for index , patch in zip(range(len(ax.patches)), ax.patches):
        if isinstance(patch, mpl.patches.Polygon) == True:
            patch.remove()
    ax.lines[:]=[]
    applyAxCorrection(ax)
```

```

def clearAxPolygonPatches(ax):

    # Get indices cooresponding to the polygon patches
    for index , patch in zip(range(len(ax.patches)), ax.patches):
        if isinstance(patch, mpl.patches.Polygon) == True:
            patch.remove()
    ax.lines[:]=[]
    applyAxCorrection(ax)

class Single_PHO_Input:
    def __init__(self, drone_info = [] , source = None, target=None):
        self.drone_info = drone_info
        self.source      = source
        self.target      = target

    def get_drone_pis (self):
        return [self.drone_info[idx][0] for idx in range(len(self.drone_info)) ]

    def get_drone_uis (self):
        return [self.drone_info[idx][1] for idx in range(len(self.drone_info)) ]

    def get_tour(self, algo, plot_tour_p=False):
        return algo( self.drone_info,
                     self.source,
                     self.target,
                     plot_tour_p      )

    # Methods for \verb|ReverseHorseflyInput|
    def clearAllStates (self):
        self.drone_info = []
        self.source = None
        self.target = None

def single_pho_run_handler():
    import random
    def wrapperEnterRunPoints(fig, ax, run):
        def _enterPoints(event):
            if event.name      == 'button_press_event'          and \
               (event.button   == 1 or event.button == 3)       and \
               event.dblclick == True and event.xdata  != None and event.ydata  != None:

                if event.button == 1:
                    # Insert blue circle representing the initial position of a drone
                    print Fore.GREEN
                    newPoint = (event.xdata, event.ydata)
                    speed     = np.random.uniform() # float(raw_input('What speed do you want for the drone at '+str(ne
                    run.drone_info.append( (newPoint, speed) )
                    patchSize = (xlim[1]-xlim[0])/40.0
                    print Style.RESET_ALL

                    ax.add_patch( mpl.patches.Circle( newPoint, radius = patchSize,
                                                       facecolor='#b7e8cc', edgecolor='black'  ))

                    ax.text( newPoint[0], newPoint[1], "{:.2f}".format(speed), fontsize=15,
                           horizontalalignment='center', verticalalignment='center' )

                    ax.set_title('Number of drones inserted: ' +\
                                str(len(run.drone_info)), fontdict={'fontsize':25})

```

```

elif event.button == 3:
    # Insert big red circles representing the source and target points
    patchSize = (xlim[1]-xlim[0])/50.0
    if run.source is None:
        run.source = (event.xdata, event.ydata)
        ax.add_patch( mpl.patches.Circle( run.source, radius = patchSize,
                                           facecolor= '#ffd9d6', edgecolor='black', lw=1.0 ))
        ax.text( run.source[0], run.source[1], 'S', fontsize=15,
                 horizontalalignment='center', verticalalignment='center' )

    elif run.target is None:
        run.target = (event.xdata, event.ydata)
        ax.add_patch( mpl.patches.Circle( run.target, radius = patchSize,
                                           facecolor= '#ffd9d6', edgecolor='black', lw=1.0 ))
        ax.text( run.target[0], run.target[1], 'T', fontsize=15,
                 horizontalalignment='center', verticalalignment='center' )

    else:
        print Fore.RED, "Source and Target already set", Style.RESET_ALL
# Clear polygon patches and set up last minute \verb|ax| tweaks
clearAxPolygonPatches(ax)
applyAxCorrection(ax)
fig.canvas.draw()
return _enterPoints

# The key-stack argument is mutable! I am using this hack to my advantage.
def wrapperkeyPressHandler(fig, ax, run):
    def _keyPressHandler(event):
        if event.key in ['i', 'I']:

            # Select algorithm to execute
            algo_str = raw_input(Fore.YELLOW                                +\
                                "Enter algorithm to be used to compute the tour:\n Options are:\n" +\
                                " (odw)      One Dimensional Wavefront \n"      +\
                                Style.RESET_ALL)

            algo_str = algo_str.lstrip()

            # Incase there are patches present from the previous clustering, just clear them
            clearAxPolygonPatches(ax)
            if algo_str == 'odw':
                tour = run.get_tour( algo_odw, plot_tour_p=True )
            else:
                print "Unknown option. No horsefly for you! ;-D "
                sys.exit()
            applyAxCorrection(ax)
            fig.canvas.draw()

        elif event.key in ['c', 'C']:
            # Clear canvas and states of all objects
            run.clearAllStates()
            ax.cla()

            applyAxCorrection(ax)
            ax.set_xticks([])
            ax.set_yticks([])

            fig.texts = []
            fig.canvas.draw()

```

```

        return _keyPressHandler

# Set up interactive canvas
fig, ax = plt.subplots()
run = Single_PHO_Input()

from matplotlib import rc

# specify the custom font to use
plt.rcParams['font.family'] = 'sans-serif'
plt.rcParams['font.sans-serif'] = 'Times New Roman'

xlim = utils_graphics.xlim
ylim = utils_graphics.ylim

ax.set_xlim([xlim[0], xlim[1]])
ax.set_ylim([ylim[0], ylim[1]])
ax.set_aspect(1.0)
ax.set_xticks([])
ax.set_yticks([])

ax.set_title("Enter drone positions, source and target onto canvas. \n \
(Enter speeds into the terminal, after inserting a drone at a particular position)")

mouseClick = wrapperEnterRunPoints (fig,ax, run)
fig.canvas.mpl_connect('button_press_event' , mouseClick)

keyPress = wrapperkeyPressHandler(fig,ax, run)
fig.canvas.mpl_connect('key_press_event', keyPress )

plt.show()

class Multiple_PHO_Input:
    def __init__(self, drone_info = [] , sources = [], targets=[]):
        self.drone_info = drone_info
        self.sources = sources
        self.targets = targets

    def get_drone_pis (self):
        return [self.drone_info[idx][0] for idx in range(len(self.drone_info)) ]

    def get_drone_uis (self):
        return [self.drone_info[idx][1] for idx in range(len(self.drone_info)) ]

    def get_tour(self, algo, plot_tour_p=False):
        return algo( self.drone_info,
                     self.sources,
                     self.targets,
                     plot_tour_p )

# Methods for \verb|ReverseHorseflyInput|
def clearAllStates (self):
    self.drone_info = []
    self.sources = []
    self.targets = []

```

```

def multiple_pho_run_handler():
    import random
    def wrapperEnterRunPoints(fig, ax, run):
        def _enterPoints(event):
            if event.name == 'button_press_event' and \
               (event.button == 1 or event.button == 3) and \
               event.dblclick == True and event.xdata != None and event.ydata != None:

                if event.button == 1:
                    # Insert circle representing the initial position of a drone
                    print Fore.GREEN
                    newPoint = (event.xdata, event.ydata)
                    speed = np.random.uniform() # float(raw_input('What speed do you want for the drone at '+str(ne
                    run.drone_info.append( (newPoint, speed) )
                    patchSize = (xlim[1]-xlim[0])/40.0
                    print Style.RESET_ALL

                    ax.add_patch( mpl.patches.Circle( newPoint, radius = patchSize,
                                                       facecolor='#EBEBEB', edgecolor='black' ))

                    ax.text( newPoint[0], newPoint[1], "{:.2f}".format(speed), fontsize=10,
                           horizontalalignment='center', verticalalignment='center' )

                    ax.set_title('Number of drones inserted: ' +\
                                str(len(run.drone_info)), fontdict={'fontsize':25})

                elif event.button == 3:
                    # distinct colors, obtained from https://sashat.me/2017/01/11/list-of-20-simple-distinct-colors/
                    cols = ['#e6194b', '#3cb44b', '#ffe119', '#4363d8', '#f58231',
                           '#911eb4', '#46f0f0', '#f032e6', '#bcf60c', '#fabeb4',
                           '#008080', '#e6beff', '#9a6324', '#fffac8', '#800000',
                           '#aaffc3', '#808000', '#ffd8b1', '#000075', '#808080']

                    # Insert big colored circles representing the source and target points

                    patchSize = (xlim[1]-xlim[0])/50.0
                    if (len(run.sources) + len(run.targets)) % 2 == 0 :
                        run.sources.append((event.xdata, event.ydata))
                        ax.add_patch( mpl.patches.Circle( run.sources[-1], radius = patchSize,
                                                           facecolor= cols[len(run.sources) % len(cols)], edgecolor='black'
                        ax.text( run.sources[-1][0], run.sources[-1][1], 'S'+str(len(run.sources)), fontsize=15,
                               horizontalalignment='center', verticalalignment='center' )

                    else :
                        run.targets.append((event.xdata, event.ydata))
                        ax.add_patch( mpl.patches.Circle( run.targets[-1], radius = patchSize,
                                                           facecolor= cols[len(run.sources)%len(cols)], edgecolor='black'
                        ax.text( run.targets[-1][0], run.targets[-1][1], 'T'+str(len(run.targets)), fontsize=15,
                               horizontalalignment='center', verticalalignment='center' )

                    # Clear polygon patches and set up last minute \verb|ax| tweaks
                    clearAxPolygonPatches(ax)
                    applyAxCorrection(ax)
                    fig.canvas.draw()
        return _enterPoints

```

```

# The key-stack argument is mutable! I am using this hack to my advantage.
def wrapperKeyPressHandler(fig, ax, run):
    def _keyPressHandler(event):
        if event.key in ['i', 'I']:

            # Select algorithm to execute
            algo_str = raw_input(Fore.YELLOW                                +\
                                "Enter algorithm to be used to compute the tour:\n Options are:\n"  +\
                                " (replib)      Repeated bottleneck matching \n"                +\
                                Style.RESET_ALL)

            algo_str = algo_str.lstrip()

            # Incase there are patches present from the previous clustering, just clear them
            clearAxPolygonPatches(ax)
            if algo_str == 'replib':
                tour = run.get_tour( algo_replib, plot_tour_p=True )
            else:
                print "Unknown option. No horsefly for you! ;-D "
                sys.exit()
            applyAxCorrection(ax)
            fig.canvas.draw()

        elif event.key in ['c', 'C']:
            # Clear canvas and states of all objects
            run.clearAllStates()
            ax.cla()

            applyAxCorrection(ax)
            ax.set_xticks([])
            ax.set_yticks([])

            fig.texts = []
            fig.canvas.draw()
    return _keyPressHandler

# Set up interactive canvas
fig, ax = plt.subplots()
run = Multiple_PHO_Input()

from matplotlib import rc

# specify the custom font to use
plt.rcParams['font.family'] = 'sans-serif'
plt.rcParams['font.sans-serif'] = 'Times New Roman'

xlim = utils_graphics.xlim
ylim = utils_graphics.ylim

ax.set_xlim([xlim[0], xlim[1]])
ax.set_ylim([ylim[0], ylim[1]])
ax.set_aspect(1.0)
ax.set_xticks([])
ax.set_yticks([])

ax.set_title("Enter drone positions, sources and targets onto canvas.")

mouseClick = wrapperEnterRunPoints (fig,ax, run)
fig.canvas.mpl_connect('button_press_event' , mouseClick)

```



```
keyPress      = wrapperkeyPressHandler(fig,ax, run)
fig.canvas.mpl_connect('key_press_event', keyPress  )

plt.show()
```

◇

Fragment referenced in [3](#).
Uses: [algo_odw 10](#), [algo_repbot 14a](#).

Appendix F

Implementation of $\langle \text{Plotting} \rangle$

We typically plot the tours onto a separate window if the boolean switch `plot_tour_p` is set to `True` while calling the algorithm. The path of the package is shown in bold red. The paths of the drones from their initial positions to the point where they pick up the package from another drone are shown in blue.

An example output from the `plot_tour` function is shown below.

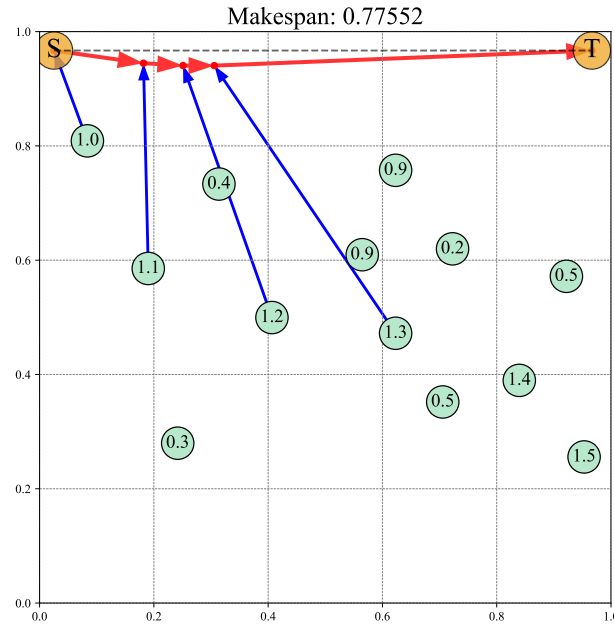


Figure F.1: The numbers inside the circle indicate the speed of the drone

$\langle \text{Plotting } 30 \rangle \equiv$

```
def plot_tour(fig, ax, figtitle, source, target,
              drone_info, used_drones, package_trail,
              xlims=[0,1],
              ylims=[0,1],
              aspect_ratio=1.0,
              speedfontsize=10,
              speedmarkersize=20,
              sourcetargetmarkerfontsize=15,
              sourcetargetmarkersize=20 ):
```

```

import matplotlib.ticker as ticker
ax.set_aspect(aspect_ratio)
ax.set_xlim(xlims)
ax.set_ylim(ylims)

plt.rc('font', family='serif')

# Draw the package trail
xs, ys = extract_coordinates(package_trail)
ax.plot(xs,ys, 'ro', markersize=5 )
for idx in range(len(xs)-1):
    plt.arrow( xs[idx], ys[idx], xs[idx+1]-xs[idx], ys[idx+1]-ys[idx],
               **{'length_includes_head': True,
                  'width': 0.007 ,
                  'head_width':0.025,
                  'fc': 'r',
                  'ec': 'none',
                  'alpha': 0.8})

# Draw the source, target, and initial positions of the robots as bold dots
xs,ys = extract_coordinates([source, target])
ax.plot(xs,ys, 'o', markersize=sourcetargetmarkersize, alpha=1.0, ms=10, mec='k', mfc='#F1AB30' )
#ax.plot(xs,ys, 'k--', alpha=0.6 ) # light line connecting source and target

ax.text(source[0], source[1], 'S', fontsize=sourcetargetmarkerfontsize,\
        horizontalalignment='center',verticalalignment='center')
ax.text(target[0], target[1], 'T', fontsize=sourcetargetmarkerfontsize,\
        horizontalalignment='center',verticalalignment='center')

xs, ys = extract_coordinates( [ drone_info[idx][0] for idx in range(len(drone_info)) ] )
ax.plot(xs,ys, 'o', markersize=speedmarkersize, alpha = 1.0, mec='None', mfc='#b7e8cc' )

# Draw speed labels
for idx in range(len(drone_info)):
    ax.text( drone_info[idx][0][0], drone_info[idx][0][1], format(drone_info[idx][1],'.2f'),
            fontsize=speedfontsize, horizontalalignment='center', verticalalignment='center' )

# Draw drone path from initial position to interception point
for pt, idx in zip(package_trail, used_drones):
    initdroneposn = drone_info[idx][0]
    handoffpoint = pt

    xs, ys = extract_coordinates([initdroneposn, handoffpoint])
    plt.arrow( xs[0], ys[0], xs[1]-xs[0], ys[1]-ys[0],
               **{'length_includes_head': True,
                  'width': 0.005 ,
                  'head_width':0.02,
                  'fc': 'b',
                  'ec': 'none'})

fig.suptitle(figtitle, fontsize=15)
ax.set_title('\nMakespan: ' + format(makespan(drone_info, used_drones, package_trail),'.5f'), fontsize=16)

startx, endx = ax.get_xlim()
starty, endy = ax.get_ylim()

```

```

ax.tick_params(which='both', # Options for both major and minor ticks
               top='off', # turn off top ticks
               left='off', # turn off left ticks
               right='off', # turn off right ticks
               bottom='off') # turn off bottom ticks

# Customize the major grid
ax.grid(which='major', linestyle='-', linewidth='0.1', color='red')
ax.grid(which='minor', linestyle=':', linewidth='0.1', color='black')

#ax.xaxis.set_ticks(np.arange(startx, endx, 0.4))
#ax.xaxis.set_major_formatter(ticker.FormatStrFormatter('%0.1f'))

#ax.yaxis.set_ticks(np.arange(starty, endy, 0.4))
#ax.yaxis.set_major_formatter(ticker.FormatStrFormatter('%0.1f'))

plt.yticks(fontsize=5, rotation=90)
plt.xticks(fontsize=5)

# A light grid
plt.grid(color='0.5', linestyle='--', linewidth=0.5)

```

◇

Fragment referenced in [3](#).

Todo list

TODO!	4
TODO!	5