FUNDAMENTALS OF DIGITAL TWINS APPLIED TO A PLASTIC TOY BOAT AND A SHIP SCALE MODEL

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ABSTRACT

The objective of this paper is to present some fundamentals of digital twins that can be applied to examples ranging in different degrees of complexity. The paper presents a common definition of the digital twin concept to examine what are its main elements and how they interact with each other. Such elements are applied to a simple example with a digital twin of a floating body based on computer vision, developed with open source libraries and a web-based approach.

Moving towards a more complex example, the paper presents a digital twin of a ship scale model in waves. The model is equipped with a dynamic positioning system, allowing remote control of the desired setpoint from the digital twin interface. Finally, as a direction for future work, the paper discusses the early efforts on the creation of a digital twin of the research vessel Gunnerus based on the aggregation of data from various instrumentation devices.

ELEMENTS OF A DIGITAL TWIN

The origins of the digital twin concept can be traced to the aerospace and defense industries, with proponents such as NASA and the US DoD. In a draft roadmap from 2010 outlining planned developments (Shafto et al. 2010, p. 18), NASA defines the concept as:

"an integrated multiphysics, multiscale simulation of a vehicle or system that uses the best available physical models, sensor updates, fleet history, etc., to mirror the life of its corresponding flying twin."

By aggregating such information, the digital twin would provide operational support in various ways. The report presents four of its expected use cases: simulate a mission before it is actually executed, mirror the behavior of its physical twin during operation, perform in-situ forensics of a potentially catastrophic fault or damage, and serve as a platform for studying the effects of modifications in mission parameters which were not considered during design phase.

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To translate the digital twin concept to practical applications, it becomes relevant to identify what are its main principles and elements in the context of engineering problems. In fact, the digital twin is guided by the underlying principle of using a simulation to reproduce the physical constitution and behavior of a physical asset, with the purpose of supporting its operation.

Attempts to classify the composition of a digital twin data contents usually converge to a typology based on three main groups: asset representation, behavioral models and measured data (Cameron et al. 2018; Cabos and Rostock 2018). This last category can be further broken down into data describing the asset's state and data describing its surrounding context, whether operational, environmental or other (Erikstad 2017). Figure 1 presents the elements of a digital twin according to that framework.

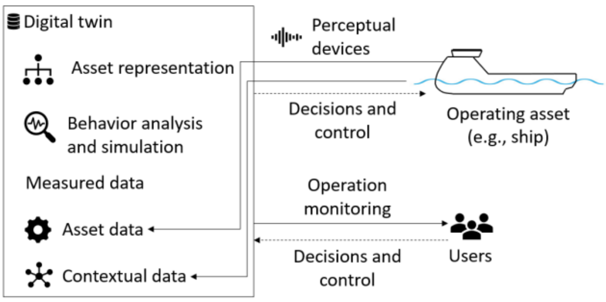

Figure 1: A General Digital Twin Framework

These three main data groups need to be closely aligned in order to interact effectively and fulfill the intended digital twin purpose, so their contents will be to some degree dependent on the domain of interest. In general, the asset representation will commonly include a geometric 3D model of the asset, which can be complemented with relevant metadata about the component description, weight distribution and material models.

The behavior models help the digital twin users to derive operational insight about the asset. Such models offer analyses and simulations that use the measured data to bridge the digital asset representation to the physical reality. The linking of behavior to the measured data can happen in different manners. A model which feeds directly from sensor log streams can be used for near real-time operation support. On the other hand, historic data can be used to estimate the current asset condition or analyze its performance in previous operations, among others.

The states modelled with measured data can include inspection reports and other information manually entered to the digital twin system. With the advances in technologies for smart devices and internet of things, the novel value of a digital twin will be on extracting insight from sensors and other perceptual devices rather than simply archiving report documents. Some digital twins may also offer the possibility to control the physical asset, though this will not necessarily be a feature of all implementations. For this reason, Figure 1 represents this functionality with dashed lines.

Figure 1 will be used as a template to instantiate the digital twin examples presented in the next sections. The examples employ an open approach as far as possible, allowing collaboration and modification of the source code by interested parties. The digital twin graphic interfaces are developed as web applications. The choice to use a web-based approach is due to reasons which were developed in a previous paper by the authors (Fonseca and Gaspar 2019). In short, web simulations are highly compatible across devices and operating systems due to their reliance on widely adopted open standards such as HTML and JavaScript; they can be shared and accessed across geographically distributed users and their development can make use of various open libraries for multiple purposes, such as performing analyzes and creating visualizations.

A SIMPLE DIGITAL TWIN OF A FLOATING BODY – A PLASTIC TOY BOAT

Digital Twin Setup and Functionality

The digital twin aims to provide a monitoring interface for the motion of a floating object, in this case a toy boat. Figure 2 illustrates the digital twin data flow. The physical setup of the experiment consists in a small aquarium inside which the boat floats. During the data collection (1.), a consumer webcam captures the boat moving in the scene. The webcam streams the captured video to a client (2.). The client executes the digital twin simulations in real-time on a web browser. In (3.), the client processes the webcam video with a computer vision algorithm to identify and track the boat on a two-dimensional plane with translation (surge, heave) and rotation (pitch). For simplification of the setup, the image gathering and client execution were performed in the same machine, a basic consumer laptop. Alternatively, the camera image could be streamed over a network to share the digital twin with various users.

Once the digital twin can parse the boat movement automatically, it is possible to use the position coordinates to support different functionalities. In (4.), they are monitored with a 3D visualization and a motion plot updated in real-time. This monitoring can be linked to automated reasoning based on the tracked variables, e.g., by making the digital twin automatically emit a warning in case the boat motion crosses a user-specified threshold.

Asset Representation

In a digital twin, the digital asset representation is used to mirror the “life” of a real asset. Given the boat’s “life” in this example is simply its two-dimensional kinematics as a rigid body, a 3D geometry with the same physical proportions as the toy boat suffices as asset representation. The 3D visualization presented in this work are created with Three.js, an open source library that simplifies creation of WebGL scenes and animations (https://threejs.org/).

Simulation and Visualization of Asset Behavior

The digital twin should include behavioral models that make use of the data perceived from the physical reality. Thus, in a digital twin the behavioral model is closely related to the perceived data: it should receive a data log and represent it as a meaningful behavior. According to the overall purpose of this example, the digital models for asset behavior should digitally represent the boat motion captured with the camera. To fulfill that purpose, a 3D visualization and a motion plot were created to show the boat motion with the digital twin.

The 3D visualization shows an ocean environment representing the aquarium. It is rendered with water textures and reflection, sky textures and illumination positioned to represent sunlight. It is based on a work

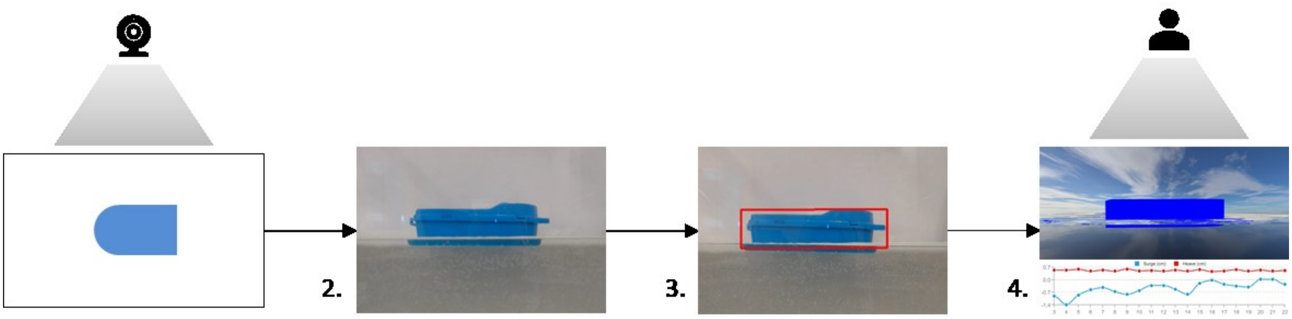

Figure 2: Data Gathering, Transmission, Processing and Usage for the Digital Twin of the Toy Boat

which allowed the user to quickly visualize the motion response of a ship to regular waves (Chaves and Gaspar 2016). In another previous work, it also adapted for usage with the Vessel.js open source library for ship design and simulation (Fonseca et al. 2019). The visualization reused several open source scripts, whose authorship is attributed inside the digital twin repository. Figure 3 shows the 3D digital twin visualization, with the boat representation described in the previous section floating on the water surface. Since the digital twin presented here is not capable of perceiving the water motion inside the aquarium, the water surface in this example is always still.

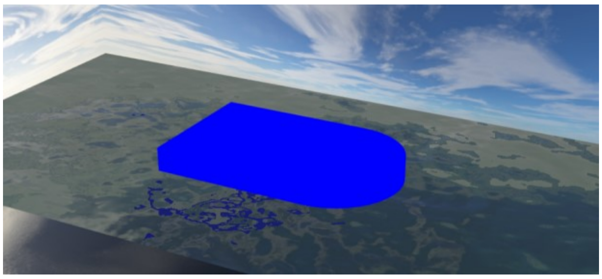

Figure 3: Perspective of the Digital Twin Visualization

As the digital twin receives the coordinates for the three degrees of freedom (DOF) considered in this example, i.e., surge, heave and pitch, the visualizations are updated accordingly. The 2D motion plot displays the current boat coordinates in the time series, while the 3D visualization animates the boat model with new geometry position. The web application executes these operations several times per second, resulting in a responsive simulation showing the motion behavior in near real-time.

Measured Data: Rendering Raw Image into Net Positions

Having the asset representation and the behavior visualizations as the basis for the motion tracking digital twin, let us now investigate the measured data, its role, capture, processing and usage. The digital twin in this example aims to represent the boat motion in real time, so the measured data needs to be handled as a stream log of coordinates (two planar and one rotational) that can be immediately linked to the visualizations. However, in order to obtain that stream, the raw data as captured by the perception device needs to be processed into net data that grasps the physical variables of interest. In this example, this translates to converting the VGA video captured by the web camera to the boat movement in spatial coordinates. This conversion can be performed by calibrating a physical setup for the image recording and then applying a computer vision algorithm to the captured image.

The calibration of the physical setup ensures a consistent and known relation between the physical motion of the boat and the motion of the track box in the video processed from the camera. For that purpose, the camera was installed in a fixed position by the side of the aquarium in order to capture the boat movements of interest. The mid-section of the aquarium was measured with rulers and a cardboard sheet was placed on that position. The cardboard contained lines of known length that allowed the correspondence between the physical distance on the middle plane of the aquarium and the corresponding pixel distance on the captured video. This calibration method does not account for eventual radial or tangential distortions on the image recorded by the camera. To minimize inaccuracies in the motion tracking, the boat is tied to mooring lines which avoid it from drifting away from the region used as calibration target.

Once the physical setup is arranged to ensure consistent and reliable gathering of raw data, we can proceed to render the raw data into net data, i.e., obtain the movement coordinates from the video source. The OpenCV.js library was used to perform the image processing and motion tracking. OpenCV (Open Source Computer Vision Library) is an open source library for computer vision and machine learning (https://opencv.org/). The library is written in C++, but the JavaScript binding offers a subset of the available algorithms, allowing them to be executed directly on the web browser.

More specifically, the example tracks the boat motion with the Camshift algorithm (Bradski 1998). Camshift is based on another algorithm, Meanshift, which identifies objects on video by performing a histogram analysis of image colors and then tracks its motion on the following video frames. Camshift adapts Meanshift by calculating also the size and rotation of the window that best fits the object in the scene. This allows its usage to track also the rotational motion of the boat but tends to make the tracking less stable compared to Meanshift. For the example presented here, Camshift worked reliably given the appropriate object color and scene illumination. The reader can consult the algorithm configuration parameters in the repository linked by the end of the paper.

Results

With all digital twin elements working in conjunction, it is possible to recognize the object on the image, convert its pixel positions to physical coordinates and display those physical coordinates in the visualizations in real-time. For this reason, it is possible to say that the digital twin worked as conceived: it was able to reliably recognize and track the ship model, while the visualizations followed the movement in near real-time for monitoring purposes.

Figure 4 illustrates the digital twin functionality. It shows a screenshot of the web interface with the object tracking box, on the left side, and the corresponding 2D and 3D digital twin visualizations, on the right one. All the simulation algorithms were executed on a web browser running on a basic consumer laptop.

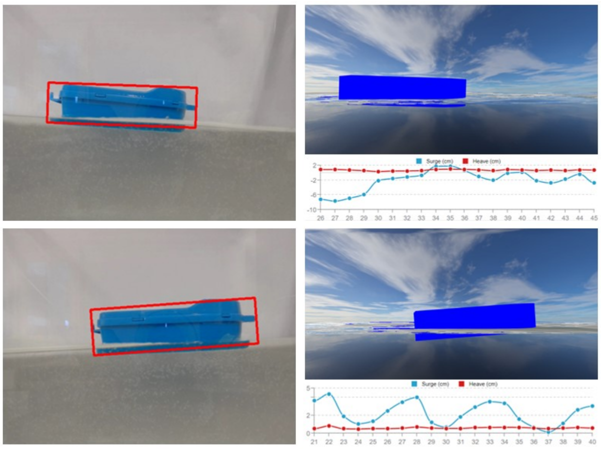

Figure 4: Screenshots of the Digital Twin Interface

Despite this application being a very simple example of a digital twin, it can still be traced to the use case of mirroring the behavior of an asset during operation. It can also be expanded to cover in-situ forensics. For example, the boat positions retrieved as numeric values can be compared with specified thresholds so the operator can be warned in case there is a large response leading to excessive drift or risk of green water.

It is interesting to note that, in this case study, the usage of a single imaging sensor allowed the extraction of three motion modes of a floating object. These results emphasize the importance of purposeful planning and usage of perceptual devices for the creation of digital services, a finding that resonates with other works in the area (Erikstad 2019; Nokkala et al. 2019).

In order to make the jump from mirroring and analyzing current behavior to also predicting and achieving a desired future behavior, the digital twin needs to include data and models that estimate or, ideally, control the asset behavior in prospective situations. The following section gives an example of how this can be achieved.

DIGITAL TWIN OF A SHIP SCALE MODEL

Digital Twin Setup and Functionality

The digital twin in this study case aims to monitor and control a ship scale model navigating in a wave basin. The experiments were performed in the Numerical Offshore Tank at University of São Paulo (TPN-USP). Figure 5 depicts the wave basin, measuring 14 meters on each side and 4.1 meters of depth. It is equipped with flaps that allow generation of regular and irregular waves from a user-specified direction surrounding the scale model. The flaps also work as wave absorbers to minimize interference of wave reflection in the desired wave characteristics.

Figure 5: The Numerical Offshore Tank at University of São Paulo (TPN-USP) (Mello 2012)

Figure 6 shows the scale model used in the experiment, which represents a platform supply vessel. It is actuated with a dynamic positioning (DP) system comprising two azimuth propellers and a bow tunnel thruster.

Figure 6: PSV Scale Model Used in the Experiment (Ianagui 2019)

The development of the digital twin system followed a bottom-up approach where several subsystems, models and data files already in use on the TPN workflow were aggregated into an overarching architecture. Figure 7 outlines the digital twin framework applied to this example, listing the elements considered for each category. They are detailed in the following sections.

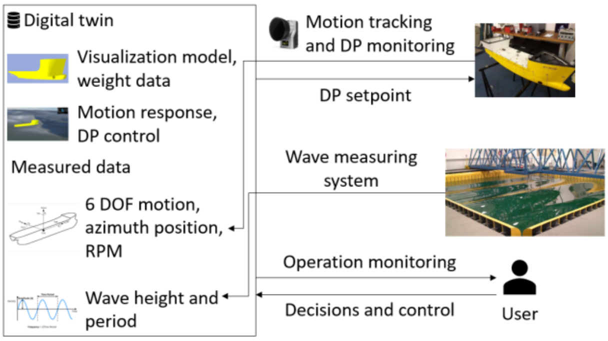

Figure 7: Digital Twin Framework Applied to Experiment with the Scale Model

Asset Representation

The asset representation is again based on a visualization of the ship model, but this time also detailing the installed DP system. It is composed of three different models: hull, azimuth case and propeller.

The hull was obtained by converting the original CAD files to the STL format, which is suitable for 3D visualization and printing. The other two models were already obtained as STL files ready for the intended usage. These three models were replicated and arranged in order to assemble the final asset representation, observed in Figure 8. The assembly considered the movements necessary to represent the DP system operation: the stern systems move on the azimuth plane and the propellers rotate around their central axes.

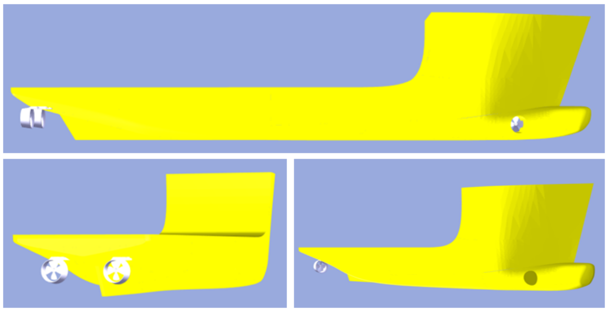

Figure 8: Visualization of the Ship Scale Model with DP System

Besides the geometric data used to create the asset visualization in this example, the manufacturing files of the ship scale model also included Excel tables containing weight data such as weight distribution and center of gravity. This data is not used in the digital twin example presented in this section, but in the future it will be incorporated to the asset representation as metadata for completeness and centralization.

Behavioral Models: Wave Motion and DP Control

The digital twin considers three main groups of relevant behaviors, two directly related to the asset itself and one to its context. The first behavioral model includes the asset motion response to waves. A visualization like the one presented in the previous study case was prepared to show the ship position on its six degrees of freedom. Additionally, a data file with the results of a motion response analysis for several wave conditions, obtained with an external software package, was linked to the digital twin so it could be used for validation and optimization functionalities.

The second group of behavior models and controls the dynamic positioning system. A separate algorithm reads the position on the scale model and controls the propulsion system to attain a desired setpoint (Ianagui 2019). The digital twin communicates with that algorithm both by receiving data with current propulsion parameters and by sending data with desired ship positioning, i.e., the setpoint. The received data allows the digital twin to show the propulsion behavior in the visualization with propeller rotation and azimuth positions. The sent data allows the user to control the ship positioning by sending a setpoint with the three coordinates on the navigation plane: x or surge, y or sway and heading or yaw.

The third and last model accounts for the incident wave. Given the wave height and period, the algorithm calculates the wavelength using the dispersion relation for deep waters. Then, the simulation animates the 3D visualization with a regular wave of corresponding characteristics. By aggregating these three models, the digital twin has the capacity to offer a centralized interface for monitoring and control of the scale model experiment, given that it is provided with the appropriate data measurements.

Measured Data

Each one of the groups of the behavioral models in the previous section is animated by a corresponding set of measured data. The TPN workflow already relied on existing systems for gathering and processing of data for each of the three groups. Such systems were incorporated to the overall digital twin functionality.

The scale model motion is tracked with a stereoscopic system which recognizes five reflective targets fixed to the object, then uses their positions to derive the model motion on six degrees of freedom. The data measuring the behavior of the dynamic positioning system was also easily obtained. The DP control system was configured to stream five parameters to the digital twin: the rotation of the three propellers per minute and the azimuth angle of both stern propellers. The motion and propulsion readings were directly linked to the 3D visualization.

On the other hand, the rendering of water elevation data into wave characteristics was not as straightforward. A probe floating inside the tank, placed near the ship model, was used to measure the wave elevation, but the measuring system had two limitations: first, the wave probe was not capable of sensing the direction of the incident wave, second, the water elevation raw data still needed to be processed into the wave height and period. A few simplifications were adopted to overcome these hindrances. The experiments were performed with regular waves coming from a single direction, and the characteristics of these waves were reconstructed based on the stream of the water elevation log. This reconstruction is performed by identifying the latest wave cycle with one crest and one valley, then calculating the wave height and period so that it can be used on the digital twin simulations.

Results

Figure 9 shows a screenshot of the digital twin visualization mirroring the behavior of the PSV scale model. The visualization can be used to monitor the motion response in 6 DOF, the propulsion system operation and the incident wave.

Figure 9: Screenshot of the Digital Twin Visualization During the Experiment

As in one of the use cases suggested by NASA, the monitoring functionality allows the digital twin to be used as a proxy for the safe and effective operation of the ship model. As the second use case suggests, several times during the experiment the digital twin was used to identify if the ship was able to keep station and test whether the propulsion system was working correctly. For instance, by inspecting the visualization, it is possible to note that the azimuths are locked to the neutral position, a detail that is difficult to observe while the physical scale model is floating during the experiment. In this case, this does not happen by an operational flaw, but by design: the azimuth positions are locked for simplification of an over-actuated problem, so only the tunnel thruster actuates in the direction transversal to the ship.

Another use case mentions the possibility of using the digital twin to predict asset behavior in a future operation. The scale model allows the user to specify a desired setpoint position for the vessel, which will be attained with the corresponding algorithm. This type of control can be allied to optimization algorithms: in one of the functionalities, the user is able to minimize one of the six motion modes of the vessel. Once the user selects the desired mode on a dropdown list, the algorithm searches for the heading that minimizes it according to the stored wave response data and automatically positions the ship with that heading in relation to the incoming wave.

The fourth and final use case mentions the possibility of using the digital twin to study effects of mission parameters that were not considered during the operation. A clear application of that example is the possibility to use the digital twin for validation by comparing the expected motion responses calculated with numerical analyses to the actual empirical response measured during operation. On a real vessel, this type of functionality may help to "close the loop" between design and operation by allowing usage of operational data to guide decisions in future designs.

When these digital twin principles are applied to real operations, it becomes desirable to include techniques to ensure that the sensors are tracking the asset behavior accurately and reliably. In that sense, research on sensor redundancy and diagnostics of erroneous readings may play an important role.

TOWARDS COMPLEX DIGITAL TWINS - ASSEMBLING A DIGITAL TWIN OF A RESEARCH VESSEL

Future research steps will focus on developing a digital twin of NTNU Research Vessel (R/V) Gunnerus, depicted in Figure 10.

Figure 10: R/V Gunnerus, Photo by Fredrik Skoglund

Several vessel systems are already instrumented, and the collected data is currently shared among university members, grouping logs according to their originating sensor. A digital representation of the vessel to be used in the digital twin is already being prepared. Figure 11 shows its preliminary visualization.

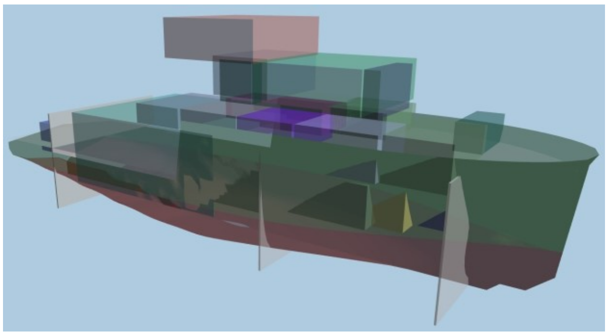

Figure 11: Preliminary Visualization for a Gunnerus Digital Twin

The research will formulate the digital twin requirements based on the research projects carried in the department, which relate to the functionalities requested by the faculty, and on the measured data currently available, which limit the types of behavioral models that can be implemented. This problem formulation will be used to analyze alternatives for the digital twin development, with the resulting models lying on the intersection between the desired and feasible use cases.

Once the stakeholders converge to a digital twin outline, a concept will be implemented with standardized taxonomies and data formats. The concept performance will be evaluated on a practical setup, opening way for identification of improvements and features for further development.

CONCLUSIONS

This paper presented a general framework based on the digital twin definition. The framework can be applied to the modelling of different digital twin examples. Here, it was applied to two study cases following a progression in complexity, the first a toy boat and the second a ship scale model. The asset representation evolves from a simple hull geometry in the first example to a ship model including hull and propeller system in the second. Similarly, the behavioral model is expanded from motion response in 3 DOF to motion response in 6 DOF with monitoring of incident wave and control of the dynamic positioning system. All the behaviors are liked to data measured from the corresponding physical experiments.

Given the novelty of the concept of an integrated digital twin and of its application to the domain of ship operations, we expect the work to contribute to future developments in this area. The study case with R/V Gunnerus, outlined as future work, will provide the opportunity to extend that contribution.

The research makes use open standards to create simulations that can be easily accessed and executed by the users. This is accomplished with web interfaces based on HTML and JavaScript that perform analyses and display visualizations tracking physical behavior in real-time. Future research efforts will focus also on standardization of digital twin data as a method to simplify development and enable reuse of digital models across projects.

SOURCE CODE

The source code for the first example is available on: https://github.com/icarofonseca/dt_cv. The source code for the second example is being prepared for publication and should be available later this year.

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