CS 452 Final Project

Louis A. Burke (laburke) and Taras V. Kolomatski (tkolomat)
July 28^{th}, 2017

Overview

When I was seven years old, I set out one day determined to discover whether on not I possessed telekinetic abilities. The conjecture was, as I outlined to myself at the time, that, noticing my decreasing level of clumsiness, one makes gestures more from memory and less from improvisation as one ages, hence the absence of this skill in adults could be explained by their being remiss to preform these experiments while young. I sat in my room and stared at objects, harbouring an intense psychological desire and focus that any *fair* universe would reward by yielding its control to my mind. *Nothing moved.*

The universe is apathetic to desire or expectation. One cannot wish a object or event into existence. It would seem that the conclusions I ought to have drawn from this investigation, paralleling the general disillusionment of childhood naïevity upon entering the adult world, would have been that the human mind is feeble and that functional living comes only from imitating the social motions of society, accidentally designed by eons of trial and error.

The lesson I learned, however, was starkly different. Suppose a benevolent universe, concerned with human life, were in place. Then the stability of an architecturally daring skyscraper, the precision of an engine, the intricacy of microchips, and the accuracy of statistical models for high energy physics, all could be handouts from the actual powers that be. Abandoning this hypothesis leads to the conclusion that mind is in fact able to modify the universe in unprecedented ways, and has at an increasing pace through history.

Through it's uncaring nature, bending to the will of no man, the universe is able to produce regularity. The task of mankind is to discover regularity, and through ingenuity, permit a three pound organ, consisting largely of fat, to shape the world through thought alone.

In the first train control milestone, we produced an accurate model of stopping distance that was defined by only two parameters (and the provided distance data).

The Experiment

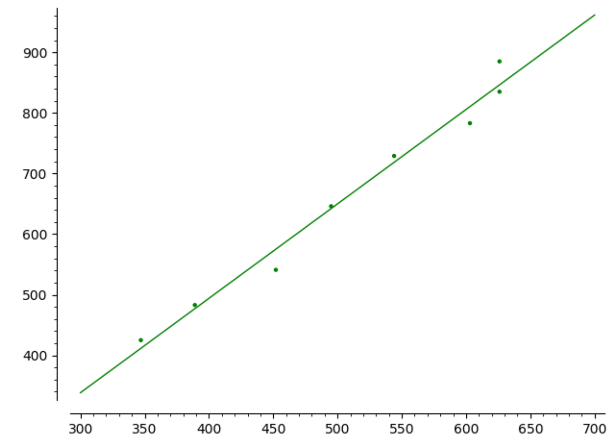
Entering this project, we were adamant that no rote measurements would be made. Particularly, if we admit that the problem of determining velocity is solved (at least in steady state), a solution to the problem of stopping a train at a given location requires solving the problem of stopping distance, thus we required a way to measure stopping distances without the use of a tape measure. The only situation in which we know the location of a train to high precision is while it is over a sensor. Thus the natural way to automate collection of stopping distances is to stop the train exactly on a sensor. We recorded the number of ticks that separated the last sensor activation and the issuing of the stop command, this allowed us to approximate the position of the train at the time of the stop command from velocity data (these were on the order of 10cm past a sensor, which is small relative to the observed stopping distances, thus allowing for error in the velocity prediction). From the distance data, this would allow us to record stopping distance within a few centimetres. This motivated us to reformulate the goal of this assignments as to be able to stop at a switch, as this problem is most well defined in the code.

Out testing program would take two points, route and flip switches as to form a loop, make a reasonable estimate of what delay after sensor A would issuing a stop command at result on the train resting a point B, determine whether we undershot or overshot, and adjust the delay, such that by trail end error we would get a data point. Impatience with waiting for results drove us to narrow our heuristic for reasonable estimates.

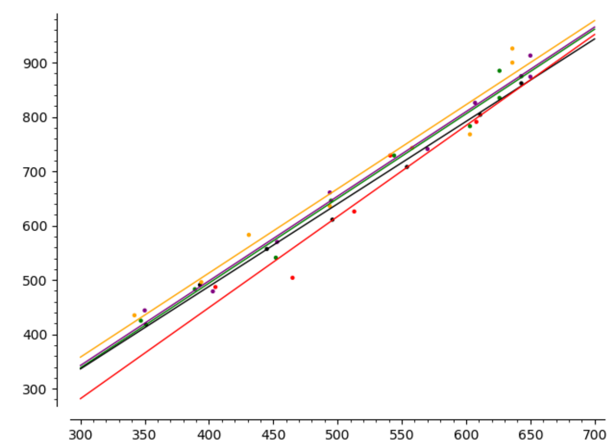
Initially, we wanted to eliminate acceleration from standstill and chose to run the loop for one full cycle before issuing a stop command. We found that the distances from point B to A that we were working with were sufficient to place the train in a steady state at the time it came to A after stopping (as seen by inter-sensor delays). Thus we eliminated all intermittent full loops, less the first, which served to gather velocity data over its full length to determine the initial estimate. We initially adjusted delays by 10 ticks on failure and would experience two errors prior to a success at general positions.

Full disclosure: *Of the 60 data points used to generate the following graphs, five starkly outlying points were pruned from the data.*

The first set of data that we compiled was for stopping distances to the sensor B2 on track A with train 70 at different speed settings. The independent variable was the incoming velocity measured over the two (justified by the desire to remove noise from data, as motivated by an careless invocation of the central limit theorem) full segments before the one in which the stop command was issued. The results were as follows:

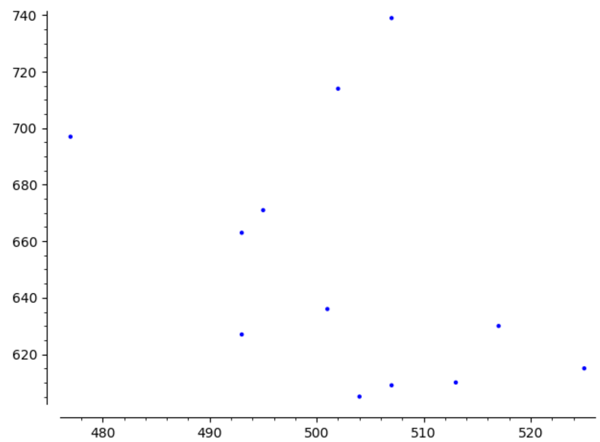


In our first observation run, we fond compelling evidence that stopping distance had a linear relation with incoming velocity. We repeated this experiment for a number of other locations on the track and compiled the data as follows:

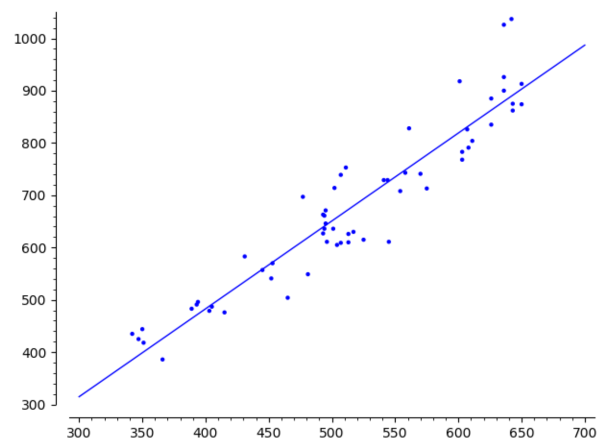


This suggests that the `a` parameter of $ax + b$ linear regressions at each point is reasonably uniform across the track.

Fitting parameters from the first regression improved our heuristics for a small number of points to correct within 15 ticks, on average. The above plot was actually made nearer to the end. Our second experiment was to alter the stopping location and to keep the set speed (10) constant. We obtained the following plot:



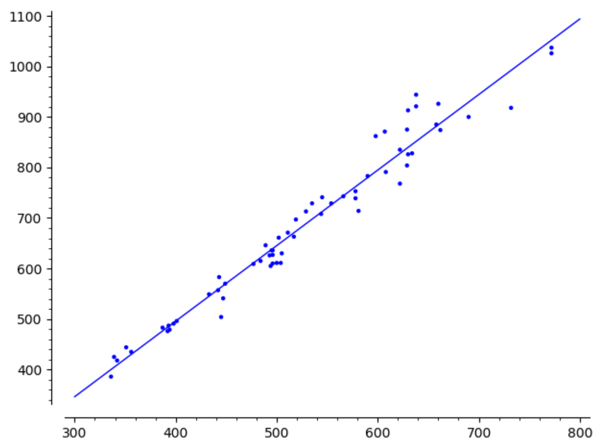
This either looks random, or strongly negatively correlated when two points are omitted. It was at this point that we gathered readings ranging over sensors and speeds, spanning an hour and a half of automated testing. We plotted the data to obtain the following:



At lower speeds, there is strong evidence of an inverse relationship between incoming speed and stopping distance within each speed class! Thus if we demoed at only one speed, as we did (because it was hard-codded; more on that later), the overall regression would not serve us at all. It would in fact be much worse than our heuristic estimates, which were at this point based off of the last four (joint incoming and outgoing) velocities observed in the calibration loop.

At this point, the investigation became difficult and proceeded down many barren paths. Generally, we were aware that track conditions of the section that we were stopping on should determine the deceleration curve. However, we thought that the incoming velocity was to be a central part of the model. We considered ratios of incoming to outgoing (over the two segments over which the stopping occurs) velocities in the calibration loop. There was no clear joint relationship between the incoming velocity, the ratio, and the stopping distance (we hoped for a $vr^\alpha + b$ model).

Finally, after trying out many sets of variables, we plotted stopping distance relative to that over the two outgoing segments in the calibration loop. We got the following graph:



This was a remarkable fit! We proceeded to test this model in our testing program and were able to consistently land exactly on the sensor in more then half of the cases, or at most with < 5 ticks of correction otherwise. This held of sections of the track that we had never passed over in the tests on which the model was based. Hence one would expect this model to work as well on track B as track A.

Analysis

We observed that speed over outgoing segments correlates very strongly with stopping distance. Let's begin by narrowing down on the definition of the independent variable. We began from steady state, by the construction of the interlacing tests, prior to point B, as such, the measurements made on the calibration loop, being the velocities measured on the route from A to B, were made in the steady state. If the train had acceleration or deceleration that was not attributed to solely track topography, the statistical evidence we have amassed would not apply.

Conjecture 0.1. *In the steady state, the velocity is able to adjust to reflecting track topography sufficiently rapidly, as such, track quality is accurately reflected by velocity in the steady state.*

Notice that the relationship in the previous graph has no clear separation between speed classes, so it appears that steady state velocity is predictive, even uniformly across different steady states. The work being done by the train's motor is not required for completeness of the description, this is very surprising.

What is more surprising is that there is a negative correlation between steady state velocities on adjacent pieces of track! We have not yet investigated this relationship to a satisfactory extent. However, we can say that it is not a matter of where on a bar the sensor hits. Velocities on segments, with the same pattern of highs and lows, remain while running the train multiples times over the same loop, as tried on several loops. It would be very unlikely that distances would be exactly consistently distorted by the train hitting one sensor with the tip of its contact tip as opposed to the tail. This would explain the negative correlations between adjacent sensors in one run. However, the plot is made with respect to incoming velocity after that calibration loop has been completed!

Structure

Our code is, at the time of this submission, in a fractured state. There are four main branches which have active development work on them.

The first branch is `dev-ai` which contains the logic for neural networks as well as fuzzy logic. These algorithms are fully functional and sufficiently performant, however they do prove to be ill suited for the task at hand.

The second branch is `dev-routing` in particular a local branch called `isolation` which contains the various servers and tasks which maintain the state of the track and choreograph train movement. One of the major servers is the position server, which maintains an accurate position for each train at any given moment. In reality it only maintains histories of sensor readings, switch positions, and train speeds, and dynamically calculates position when called for. Another important set of servers are the notification servers, these servers allow tasks to be dynamically called for various events. For example tasks can register with the senser notification server to be sent a message whenever a sensor is tripped. Similar servers exist for delays and switches.

The third branch is `taras-track-extras`. This is an active development task for calibration of trains with a simple text UI attached to it. This was the branch used for the demo as all current calibration code exists here as well as the specific code for determining stopping distance.

The fourth branch is `dev-ui` which contains a graphical user interface written in Ada as well as a set of tasks for communicating with it. This works by communicating directly over the serial port just like any other terminal, special terminal codes correspond to updates in the UI.

Algorithms

We used a number of powerful algorithms for this milestone. For routing we used dijkstra's search algorithm. Given the nature of the track, an A* search could be possible, but given that dijkstra gave very good performance we deemed it unnecessary to upgrade.

In addition to dijkstra's algorithm for routing, we have arbitrary fuzzy logic systems and multilayer perceptrons for data interpolation. These were found to be largely unnecessary. However, the neural network was mostly ported from a previous project so did not take too much time and the fuzzy logic may yet find some use.

Finally we have a simple linear interpolation producing our stopping times. This was created by having sagemath produce a linear regression on data gathered from sensors. In order to improve the accuracy of the stopping time, a long-running dynamic algorithm routes the train over a loop multiple times to precisely calibrate a stop.

Results

While we have extremely accurate stops directly on sensors that are easily extensible to offsets, this comes at a cost. In particular our stopping algorithm is an adaptation of an algorithm designed to train a neural network, and so it only works on ideal data. This means that it cannot work on paths that do not contain a loop. Additionally it gets very poor results unless it is allowed to take a full calibration loop before attempting to stop.

Meanwhile since the branch with the stopping code lacks a proper routing task, it is unable to deal with self-intersecting paths from dijkstras algorithm. Additionally it refuses to reverse a train, so at the time of presentation there were many sections of track that could not be used as stopping points.

On other branches we have a working GUI, and working notification servers, as well as partially functional position and routing servers.

Going Forward

From this milestone we have learnt that accurately modeling the trains is both easier and harder than previously anticipated. In one respect, the relationship between the physical world and the computer turned out to be remarkably straightforward. Going into this project we thought that the physical properties of the track were sufficiently disparate so as to require either many hours of data collection or else artificial intelligence (with dynamic data collection) to accurately model. Having now collected the relevant data we have found that a simple linear interpolation suffices for nearly all aspects of the system, while linear regression can accurately model everything about the tracks without need for large sample sizes.

In the coming days we intend to assimilate all of our disjoint systems and combine them with more notification and track maintenance utilities to create an accurate model.

The benefit of our current disjointed structure is that most of our utilities were designed in isolation with multiple trains in mind. As such once we successfully bind them together they should, at least in theory, work out of the box with multiple trains. Of course we expect many edge cases to present themselves, but we are hopeful that our systems will work as designed.

SHA of commit

The commit hash of the submission commit (which is on taras-track-extras) is:
`470a7955721ab450532072f926d66f99279fbb45`
The repository can be cloned from:
`gitlab@git.uwaterloo.ca:laburke/cs452_kernel.git` (SSH)
or
`https://git.uwaterloo.ca/laburke/cs452_kernel.git` (HTTPS)

There is a README in the root directory of the repository which outlines the loading command. To run the program once it is compiled just restart the machine and run `load -h 10.15.167.5 "ARM/path/to/kernel.elf"` to load it. Note that the loaded address is different from the default value.

The Program

Our kernel development defined the possibilities of interactions of tasks in the real-time system. The blocks of our system, either tasks or constituent functions, are short elementary pieces of code, themselves non-monolithic. The first train control milestone produced the fundamental structural unit of the system - a tangled logic across tasks that accomplished the goal of controlling the movement of a train. The second train control milestone implemented protocols for the interaction of two of these fundamental units. This was accomplished by setting straightforward rules, lacking intricacy and far from optimal, to ensure the units interacted correctly - that the trains controlled did not collide. Thence the control of a single train is fundamental in the sense that its parts are not units of function, and that interaction among fundamental units is far more simple then their internal complexity.

Its Overview

We have anthropomorphised the results of each previous assignment. Assignment zero was about the difficulty of communication. Kernel one was about how the context of human evolution, both biologically and sociologically, resulted in the equilibrium of society and control of its trajectory. Kernel two and three expended on the structure of this society and on the forces that must be counteracted to maintain it. Kernel four observed that the most successful communication was concise and simple.

Having produced the fundamental structural unit in the first train control milestone, we shifted away from the perspective of a human in the context of their society, to the perspective that society is just a byproduct of the inherent ingenuity of human thought. All interactions among people convey only an approximation of the complexity of the thoughts of their participants. The net effects of these sub-optimal manoeuvres could not possibly be the etiology of an individual's complexity.

The Theme

Russian mathematician Israel Gelfand delivered a lecture for his receipt of the Kyoto prize, which honours the holistic contribution to humanity of the recipient's technical work. Titled, *Two Archetypes in the Psychology of Man*, this lecture was on the the two conflicting human functions of wisdom and intellect. Wisdom is derived from experience, delivered to the individual by society. Intellect is ingenuity in fundamental opposition to the genetic and social conditioning of an individual, as observed from the patterns in society.

The outline of the lecture is as follows: Gelfand provides examples of the serious social conflicts that arise from the discrepancies of these views. This is the conflict of technocracy to the view of technology as evil, the conflict of illustrating the concept of a point to a student in saying that it is *that which has no part*, appealing to intuition, and of taking a formal axiomatic approach that enforces rigour and eschews loose intuition, the conflict of a model to the reality that it is modeling - in all technical disciples (he speaks of his experience in biology, medicine, and computer science). He postulates that the cause of these conflicts is lack of an adequate language that can express both archetypes. For example, Hilbert showed that Euclidean geometry could be placed on fully rigorous ground. If one abandons the classic definition of a point, focusing only on axiomatic relations between a point and other geometric objects, one can purify the theory. Indeed one could take points to be classical planes, and planes to be classical points - the duality of projectile geometry does not care as three generic instances of one defines a unique instance of the other. A mathematician must have both intuitive and axiomatic understanding to conceive new results, hence, although the language differs, there is no fundamental divide between the views. Gelfand explains that mathematicians are capable to and responsible for producing such a language, which must describe the abstract notion of a fundamental unit: indivisible into complex systems, and interacting mutually in a far less complicated manner.

CS 452 is a course which clashes precise theoretical models with imperfect reality, the ability to perform any single task well with the requirement that necessarily less complicated protocols govern their interaction, and the creation of elegant, suddenly inspired, solutions with the inelegant and time consuming act of debugging. Computer science is a human field of study, and, in the course of these introductions, we have explained how the field's problems are reflections of a universal psychological dilemma fundamental to the human condition.

Calibration

We know that steady state (no command related acceleration) velocity over a segment correlates well with distance traveled when stopping over the segment. In our first demo, we found these values by making a calibration loop every time we requested a train movement. We would record that the stop command be issued a certain number of ticks after a certain sensor activation. Further, we determined the progress of the train in the path it followed by counting sensor activations. Any sensor failures would be fatal to this approach, and it is not optimal to calibrate over the same segments multiple times.

We re-wrote the logic that determines progress in a path, identifying if an unusual sensor activation is the result of skipping a dead sensor. We further introduced a structure to store track calibration data. This structure records which sensors are dead and inter-sensor times. This structure allocates indexed space for storing records for all adjacent sensor pairs, and a constant number of entries for multiple segment times (with dead sensors in the middle). When running the program with no stored calibration data, we process a movement request as follows:

i. We determine if the calibration data has times for every adjacent pair in the list of live sensors on the path (all of our paths are computed as circular, which eliminates the question of what to do in the case of dead endpoints).
ii. If there is insufficient data, then run the train on a calibration route.
iii. If there is sufficient data, calculate the stopping distance and find the last live sensor on the path that can serve as a trigger to stop after a delay (if the path is short and you think that, with few dead sensors, this would be a counterexample of the existence of such a sensor, then recall that all paths are circular).

Because the map of path index to sensor ids is not necessarily injective on a circular path, the attribution logic mentioned above becomes relevant. Running over a calibration route fills in only records that do not already exist, dropping newer duplicate data. We don't loose generality by considering only circular routes without reversing, as this is a program only for calibration and maintaining steady state velocity over a track exit is impossible.

New calibration records were printed to the debug log, which was scp'ed over to our personal machines. We formatted the records to be the lines of C code that caused the records, and placed those code files in the `src/data` directory. There is a global macro to determine if the program is run in calibration mode. If it is set to false, then we run the code in `src/data`. If a calibration record does not exist at run-time, for example at the exits, then an average value is written into the structure.

Attribution and Reservation

Our attribution and reservations systems are designed to be fairly simple, yet parameterizable. This allows them to be robust, yet effective.

Our attribution system maintains the current and possible next sensors for each train. If two trains are between two sensors then only the first one will attribute to the destination, the second will only attribute there once the first successfully passes it. Then when a sensor is flipped it iterates over all of the trains in the system and decides if it was the one that flipped it. At first it merely checks the immediately following sensors of each train. If after that it can't find any match it will begin searching forward along both sensor paths to see if the activated sensor might be one of the sensors after a dead sensor. The distance ahead it looks is a specifiable constant.

Our reservation system is fairly straightforward, using a separate server to request to own sections of track and route given other train's reservations. It also provides the ability to steal sections of track to indicate that a train is misbehaving. This notifies the previous owners of those sections and lets them know that they may have to reroute. While this may not always prevent a collision, it helps to at least provide a possible response to unexpected behaviour.

An example of this is spurious sensor firings. The program can't determine which train caused it, but must assume that something did, so it should route the trains away from there - even though all trains were correctly told to avoid that location. Similarly if a train moves too slowly and gets stuck at a position on the track other trains will have to carefully route around it until it is confirmed to have been removed.

Modularization

In order to test many of the complicated subsystems in this assignment, we have transferred most of our code to a separate directory and designing it to be completely independent of our kernel and its systems. This allows us to unit test this code on our own computers - helping to get tests done when there is a lot of track contention.

Results

Unfortunately when integrating the many systems involved in this assignment, many kernel limitations were encountered which, coupled with heavy track contention in the lab, resulted in a very unstable demo.

While on rare occassions the executable loaded would successfully dynamically avoid collisions and deal with up to 4 simultaneous points of failure, for the most part it did not perform as expected.

Moving Forward

After adding extensive logs through the GUI to the project we have identified a number of the problem sources and are slowly re-integrating each module one at a time with extensive tests between each module's integration to ensure they work well with previous modules. With new log systems in place bugs are much easier to identify and development has become more streamlined.

Program Overview

Prior to the development of modern drugs that are very effective in treating epilepsy, severe cases warranted, with high efficacy, the surgical intervention of a corpus callosotomy. In this procedure, the two hemispheres of the brain were electrically isolated, effectively ceasing communication between the preferential cortex of each hemisphere, resulting in a *split brain*.

Such medical cases were of fervent interest to cognitive scientists, medical researchers, and science fiction authors. One book that I enjoyed as a child, *Peace on Earth*, by Polish author Stanisław Lem, involves a secret held by a non-verbal and non-cooperative hemisphere of the protagonist's brain, non-surgically divided by a blast from futuristic technology developed by artificial intelligences continuing the Cold War on the moon. Lem portrays the protagonist as having a *split mind* - harbouring two separate consciousnesses, with one controlling a hand that behaves much like that of *Doctor Strangelove* (Kubrick's film was released first).

However, this depiction is not accurate in the majority of cases. For example, if two objects are placed each in the field of vision belonging to each hemisphere (different eyes), then the patient will not be able to identify whether the two objects are the same. This is expected - the test of equality requires a complicated description to be conveyed between the hemispheres. However, the hand controlled by each hemisphere will correctly indicate on paper that an object is present in both visual fields. Further experiments revealed that the rate of communication between hemispheres is approximately one bit per second. This may result either by reading involuntary physical cues, or emotional cues, consistently provided to both hemispheres by a shared hind-brain. This limited communication allows patients to live a life with little to no disability in the eyes of external observers.

We conceived of a project in which we would sever an initially present networking link between the computers on which the terminals ran, representing the surgery. Subsequently, the two tracks would communicate between each other by choosing which train to send to the other track across a bridge we constructed. These messages would be processed by passing through a network of trains moving in periodic motion, and bringing the train to rest in an axon opposite to the entry point, specific to the identity of the sent train.

Automatic Transmission

The file `src/tasks/trains/transmission.c` contains the implementation of a task that is responsible for issuing commands to adjust train speed to the Märklin controller. One instance of the `transmission` task exists for each active task. Aside from the routine involved in decoding the identity of a train incoming across tracks, this task has sole agency for issuing commands to its train.

The data stored in this task is a `speed_combination`, which consists of two speeds and two durations. The transmission task issues commands to alternate between the two speeds at the specified durations. This struct is modified by the `set_speed` and `adjust_speed` functions. It is maintained such that the two speeds are adjacent integers within bounds, and such that the durations are non-negative and sum to a defined number (in our demo, this was 15 ticks). The gradation of steps by which one can adjust is also a defined number (in our case 3).

The `transmission` task receives three types of commands: set, adjust, and reverse. Delays are set by creating an asynchronous notifier such that the transmission does not block and can receive other commands. This notifier accounts for the fourth message type passed to the `transmission`. We chose to kernel panic if a reverse command was issued while the speed was not set to zero.

Defining a Schedule

The file `src/util/trains/transit_shcedule.c` contains the implementation for `TransitSchedule`, the data structure for timed routes. It contains a `RestrictedRoute`, a target velocity, an index of the last sensor visited, a list of expected arrival times, a list of observed arrival times, and a train number. Expectation values for sensors that have already been passed are meaningful only if the route begins and ends at the same sensor node.

Given the `RestrictedRoute`, target velocity, initial sensor index, and initial time, the expected times are defined at all future points in time. The expected time values are obtained from the track data under the expectation that the train will travel at the target velocity. The `init_schedule_times` method prepares the schedule given this data.

Data entry is accomplished by the `transit_register_hit` function, which takes a sensor id and time. This function will find the index of the sensor id on the route, and will panic if this is an unreasonable attribution (not explained by skipping fewer than three sensors on the route). When we said that out final demo crashed once, we meant that a misattribution occurred and the program returned to RedBoot. If the attribution is reasonable, this function will record the time (marking any missed sensors), cyclically advance the expected times (via a call to `rotate_schedule`), log the observed times, and return an integer representing the approximate distance deviation from the schedule (obtained by multiplying the target velocity by the time delta).

Since this structure is responsible for logging time records, it also provides the `transit_vel_from` function which provides velocity data over the previous specified number of segments. Overall, this structure holds and processes all the information that we need to make control decisions for trains that follow a scheduled route.

Conforming to a Schedule

The file `src/tasks/trains/conformist.c` contains three tasks: `publicTrain`, `privateTrain`, and `conform`. The first two tasks are just responsible for setting up a schedule and creating a `transmission` and `conform`. (These tasks would initialize the schedules back by 2.5s to account for acceleration.) The `conform` tasks survives for the duration of the demo and is responsible for keeping a given train on a `TransitSchedule`. It contains a parameter that allows for marking the end of a route - a feature used by `privateTrain` to end the program after the messenger train arrives at the target axon.

The `conform` task registers for sensor readings attributed to its train. It registers these readings with its `TransitSchedule`, and uses the returned distance deviation data and its requests for velocity data to make a decision of which adjustments need to be sent to the train's `transmission`. The desired behaviour is for a train to correct its deviations from the schedule and to soon loose the information of its past deviation (errors dampen and we have a guarantee of the *ergodicity* hypothesis).

Let's trace through the development of this tasks and the performance observations we made.

We began with the simplest behaviour that corrects for errors - increase velocity if we are behind and decrease velocity if we are ahead (by a minimal deviation threshold). We tested this on the route of track A's left circle. On this route, different track segments are more equal relative to a more diverse class of segment types, including straight ones, on other routes. We observed that if distance deviations were less than 40cm (approximately less than one second), then errors would dampen and deviation would oscillate with an amplitude of approximately 30 cm. However, for larger errors, we would repeatedly adjust the velocity many times before the deviation was corrected, and the excess velocity would guarantee another deviation in the opposite direction such that these errors would propagate and eventually result in a collision. Moreover, when we repeated this experiment on a different route, we saw that the non-uniformity of the track was sufficient to introduce oscillations past the observed *critical amplitude*.

Thus, we realized that, for example, if velocity data indicated that a train was going 20cm / second over the target velocity while being behind schedule by 10 cm, then the correct action would be to decrease velocity to return to the target velocity. We introduced a variable called `permissible_bound`, which gave bounds for acceptable velocity deviations, which was defined by a step function given the error returned by the call to `transit_register_hit`. This function was, with the argument in units of mm and the value in units of mm/sec:

$$f(d) = \begin{cases} 20 & |d| \leq 40 \\ 50 & 40 < |d| \leq 100 \\ 100 & 100 < |d| \leq 300 \\ 150 & |d| > 300. \end{cases}$$

The use of the `permissible_bound` depended on whether the error was greater than 50mm. For larger errors, we would read the velocity history from the last segment, and if it was within the `permissible_bound` (mono-directional - i.e. we would only reject if the deviation was large and in the direction that would result in correction), then we would issue a correction of at most three ticks (0.6 speed integers) in the direction of correcting the distance error, as a function of error. ***After the demo we discovered an error in the code*** - it was my intention to choose the number of ticks based on the difference of the observed velocity and the sum of the target velocity and bound, but we looked at the difference of observed velocity and the target velocity. This contributed to over-correction in the demo and we would probably have a much higher critical amplitude if this were corrected.

In the other case, errors less than or equal to 50mm or excess of the bound, we would issue a single tick correction in the direction of the target velocity if the bound was exceeded. On the route show in the demo, the critical amplitude was 1m (about 2.5 seconds of deviation). We consistently saw that any oscillations less than 70 cm would dampen to an oscillation of amplitude 15-30cm (depending on the train). The non uniformity of the track, and our not specifically accounting for it in the expected times, would always result in deviations of the latter magnitude. This would happen within three passes of the route. This was very within the bounds of tolerance for the demo and we were happy.

Unfortunately, oscillations on the order of a metre would propagate. Prior to the demo, we did not frequently observe errors of this magnitude. Something happened to the track within the 45 min prior the demo - train 70 did not previously get stuck at it's initial position and the deviation was entirely unexpected! The program ran smoothly four times in a row prior to our demo. If we would have observed this prior to the demo, then we would not have reset the system and not sent the train over when we saw that train 70 experienced an initial hiccup. We successfully twice demonstrated correct behaviour after three failures (twice we sent the train over after a hiccup and once we experienced a misattribution 30s after we began the program, causing a kernel panic and graceful exit to RedBoot).

Passing a Train Through the Public Transportation System

The `conform` tasks corresponding to the trains travelling in a circle constitute the *public transportation system* and are created on startup by the `publicTrain` task. When a newly introduced train was decoded and placed in its initial axon, we waited for 10s, and then launched the `privateTrain` task to create a `transition` and `conform` for the new train. Its route consisted of a fixed middle segment, appended to short beginning and ending segments that would allow us to use different axons.

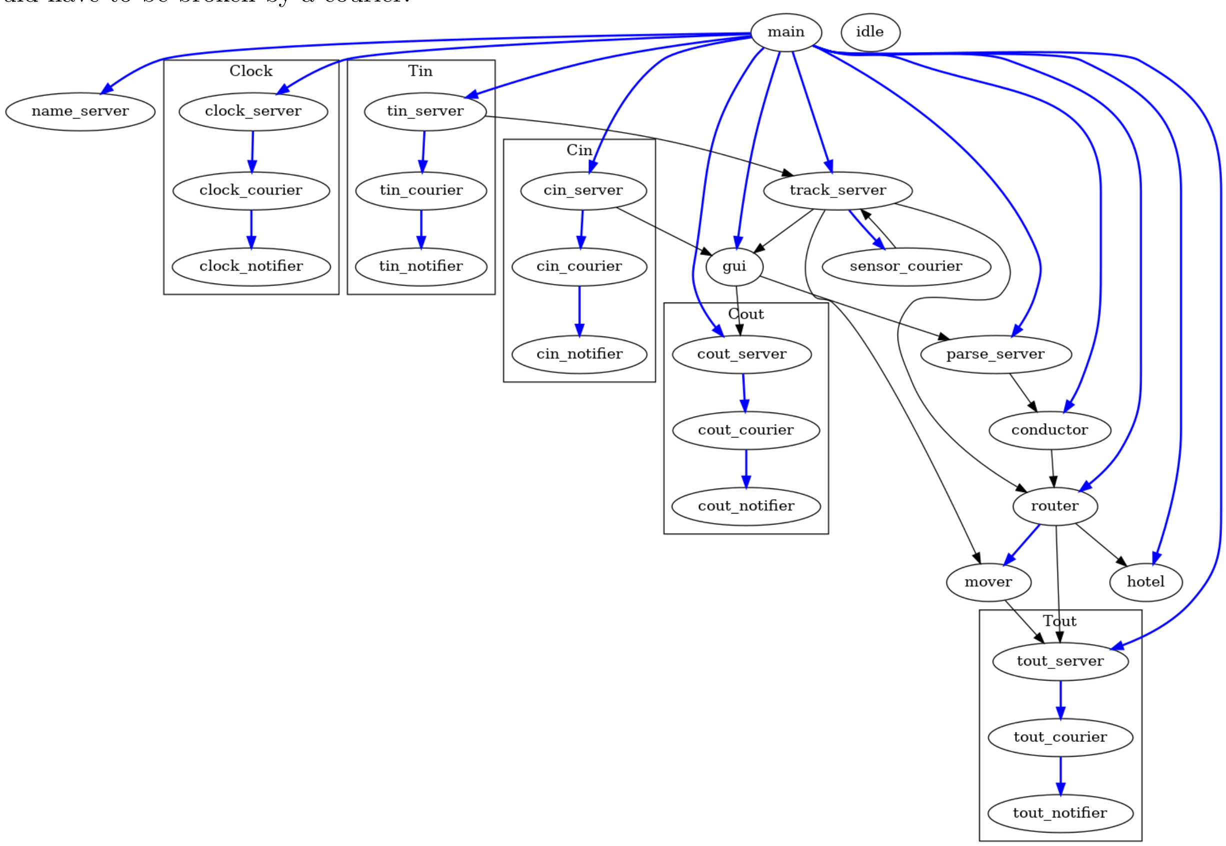
The `publicTrain` task faced the challenge of deciding at which delay to begin the `TransitSchedule`. We made this decision via the `backtrace` function. At time zero, we imagine a third *spoke* in the public transportation wheel at sensor E9, representing a hole. The `publicTrain` tasks would reply to their creator with the period at which the route was completed. We thus have a set of discrete times at which the hole is at sensor E9. The `privateTrain` task chose the initial delay such that the expected arrival time of the messenger train at sensor D10 (opposite E9 on the merge and very nearby) coincided with the soonest point in this set that is achievable from the current time.

We stopped the train a short while prior to arriving at the terminal axon, and, after a delay, we issued the STOP command to the controller. This command was indeed sent, but usually not correctly handled by the controller - the first successful run in the demo was the only time that the command successfully issued. Note that we delayed for 0.2s after issuing this command before returning to RedBoot - we think that the error is endemic to the hardware, related to processing this command while the controller is replying with sensor readings.

Exitting and Scheduling

During the first train control milestone, and persisting thereafter there were a few bugs caused by exited tasks leaving behind problems. Once these bugs were identified, the exit syscall was extended. This involved checking blocked tasks to see if any are waiting on the exiting task to continue. In these cases their intertask communication calls are aborted with the appropriate exit codes.

This also led to a slight modification of the scheduler and in general made us aware of concurrency issues. In particular we realized that the server which required the modification to be made could also cause a deadlock by sending to a task trying to send back. In order to help ensure consistent communication between tasks we created the following diagram of the major tasks to discover where concurrency issues would have to be broken by a courier.



After analyzing the earlier form of said diagram, a cyclic dependency was discovered with respect to the `gui` task and the `track_server` task. This dependency was broken by special courier allocation and reordering creation of tasks.

Regrets

The main aspect of our code that we regret is our focus on performance. Given the emphasis on performance and competitive nature of our team members, we strived to produce the most performant code possible, and this sometimes meant that robustness was a secondary concern. You may note that performance is listed below as one of the things of which we are most proud. This is still true. We are proud of our performance, but wish that we could have had more robustness as well.

Some of the areas in which more robustness could have been helpful are as follows.

- Return codes - We rarely check the return codes of our syscalls except where necessary. We could have found some of our bugs early had we maintained a policy of checking all syscall return values.
- Message passing - Many of our bugs have been due to poorly formed or received messages. A large proportion of the messages we send are zero-sized (for performance) with their meaning determined from the sender's tid, or merely the fact that the message has no size. However this makes it impossible to detect and recover from an error, as if a task sends zero bytes to a server waiting to hear it, there is no way for that server to realize it has the wrong message. Ideally we would tag each message with some unique value and sanity check every received message to ensure that the message received is from where we expect.
- Array bounds - As a lot of our most difficult bugs came from addressing off the end of an array, it would have been beneficial to create a robust array data type which we could use to ensure that we never access memory we don't have access to.
- General robustness - A lot of our code was not designed with failure in mind. The above cases are merely symptoms of overall code quality. While our code has very good performance qualities, it sacrifices robustness. For example many functions which could cause errors merely cause a kernel panic rather than trying to address them or returning some error code. Many functions also assume their data has a certain format without indicating as such with a comment or checking that it is the case. In general we have zero run-time assertions in place. The result is that large-scale bugs can be nearly impossible to diagnose.

The final regret is that our reservation system (the Hotel) never became fully operational. While it worked on its own as a unit, the use of it resulted in many concurrency bugs that made integrating it not worthwhile. Even the GUI had the ability to draw which sections were reserved, but this was never used as our code never reserved any sections.

Of What we are Most Proud

Performance. We put a lot of effort and very specific knowledge into optimizing the raw performance of our kernel. We were able to get our Send/Receive/Reply cycle down to just under 8 microseconds in the optimal case. This meant that we never really ran into significant performance problems while working on the project, freeing us up to focus on more difficult problems.

One way in which we improved performance was by moving to a newer compiler, so as to generate more optimized code. We also carefully optimized performance critical sections of code, such as the scheduler. One of the most useful little things we did was to manually organize the linker script so that critical segments of code appeared near each other. Once caches were turned on, this caused significant improvement in performance by reducing some cache misses.

HWIs do not trap into the kernel. We reserved 100 words of space at the top of the kernel stack for processing hardware interrupts and did not context switch into the frame of the kernel. Further, the HWI event did not even call code that we wrote in assembly for context switching - the HWI handler was short, simple, and inlined, such that the compiler directive `__attribute__((interrupt("IRQ")))`, would save and restore exactly the registers that it clobbered, and would call the `movs` instruction at return! The HWI handler's behaviors was to disable the interrupt by masking it away on the CPU (not at all dealing with the memory mapped locations that resulted in its issue) and unblocking the event handler in the scheduler. The latter did not cause re-scheduling and we were guaranteed atomicity between syscalls in user space tasks. Without this, for example, the debug log that we wrote to in memory would be susceptible to a race condition that would intersperse logs at best, and insert or remove a null-terminator at worst.

Scheduling. Despite the guidelines of the course, we wrote a slightly fairer scheduler than the raw round-robin priority first based scheduler. Our scheduler does a bit more work to allow lower priority tasks to on occasion execute even if a higher priority task is waiting. This does not prevent that task from executing, but rather has it execute more frequently then the lower priority tasks. In addition, we have real-time priority tasks which are guaranteed to execute whenever possible and before any higher priority task.

This allowed us to essentially ignore priorities while developing our solutions for the project. In general we gave more important tasks higher priorities and less important tasks lower priorities, but we didn't overly concern ourselves with exactly which priorities were given to which tasks. This is because even if an important task has a lower priority than another task, it doesn't mean it can't ever execute, it just executes less. Given that the vast majority of our execution occurs as a direct response to an interrupt, most tasks are left to execute in exactly the order of their priorities. However, if we were to accidentally create priorities such that a task would be starved, it would not be, it would merely run less often. This relieved a lot of the pressure to carefully pick task priorities.

The stopping model. Stopping models based on physics are placed on incorrect foundation, as taking the train to a stop is actually an illusion handled by software - cutting power to the track results in the same observable behaviour as suddenly issuing a reverse command. The goal, thus, is to fit to a function of the correct parameters. We discovered a remarkably tight fit to steady state velocity over the segments on which the stop would occur. More surprisingly, we discovered a inverse correlation within each speed setting of stopping distance to incoming velocity! This is because there is a negative correlation between steady state velocity on adjacent segments. We have concluded that this is caused by the placement of switches at approximately every second segment, as we have observed, with a voltmeter, that one section of rail in each switch does not provide power. The implication of this is that if a TC1 demo is made all in one speed setting, then determining stopping distance from the overall regression values applied to incoming velocity is strictly worse than using a constant value.

GUI. We created a true Graphical User Interface (GUI) in Ada by directly listening to the com port on the more powerful desktop computers in the lab. This allowed us to provide a more intuitive and powerful interface than a mere text-based UI could offer. While the introduction of a GUI caused a few bugs to present themselves, and took some time from possibly more critical features, it also unlocked powerful debugging opportunities. For example, the GUI allowed for logs to be collected more efficiently than merely dumping them to the screen during runtime.

Logs. The GUI was not the only system we used to collect logs. We also used an atomic log based system for debugging. This worked by writing a large null-terminated string directly into the ts7200's memory in a location that was largely unused. In particular we stored the log from address 0x50000 (only a few kilobytes from the top of RedBoot) to address 0x100000 (the first byte of our kernel). These could then be retrieved and read after the program completed by a separate logging program. Thus we could pump massive amounts of information into logs during performance critical sections of code without having to wait for the console UART interrupts and various task reschedulings. Additionally we could debug things at a lower level, such as scheduler progress and kernel information. These could not possibly be printed to the screen as that would require that they communicate with the I/O tasks.

Structure. The final thing about which we are proud is our code organization. Throughout the project we have strived to maintain a consistent organized file structure and avoid monolithic files. While many groups ended up with multi-thousand line files for some of the more powerful servers (like the train/track state maintenance server), we carefully modularized our code into small testable files. This helped greatly with debugging.

SHA of commits

Now that the project is done, everything is being pushed up to the git repo. As such the entire repository is effectively our submission. The actual code used exists on two branches. The UI used in the demo was created on the `dev-logging` branch with hash `1a80be424be4ab79a05807acb2cb2579319d5d00`. The public transit protocol was created on the `final-demo` branch with hash `d67465d1279f2058a1f9f86723930b34956fa389`. The repository can be cloned from:

`gitlab@git.uwaterloo.ca:laburke/cs452_kernel.git` (SSH)

or

`https://git.uwaterloo.ca/laburke/cs452_kernel.git` (HTTPS)

There is a README in the root directory of the repository which outlines the loading command. To run the program once it is compiled just restart the machine and run

```
load -h 10.15.167.5 "ARM/user/kernel.elf"
```

to load it.