Project Report
Enigma
October 20, 2015

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Guide
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Motivation
Box2D is a powerful physics engine which can be used to develop complex machinery. We intend to explore all the aspects and features of Box2D while completing our project, hence equipping ourselves to use Box2D and similar engines in any future endeavours which may require physics extensively.

Introduction
A Rube Goldberg machine is a contraption, invention, device or apparatus that is deliberately over-engineered to perform a simple task in a complicated fashion, usually including a chain reaction \cite{1}. In our project, we attempted to create such a machine. In this report, we intend to present to you the following

• Detailed description about our project
• The problems that we faced during the due course of this project
• Profiling of our code
The basic objective of doing this project is to gain good experience with the Box2D software. This is the initial design which we formulated for our project using Inkscape.
Domino-Hydraulic Press System

- The ball falls from the top on the pan, which leads to increase in pressure at that point in water
- By the concept of hydraulic press and the Pascal’s Principle, the pressure increases at every point in the fluid, so the other piston rises
- This leads to the rotation about the hinge, which in turn causes a chain of falls of the dominos
- The last domino pushes the ball on the next system and the motion of the ball continues

Conveyor belt-Paddle-Pulley system

- The ball, initially hit by the pendulum moves onto one conveyor belt, which forces it to change its speed and direction of motion such that it moves onto a second conveyor belt.
- This further forces the ball to hit the paddle. Due to the impulsive torque applied to the paddle during this collision, the paddle starts rotating.

\[ \int \tau dt = \omega \int mr^2 \, dr \]

- While rotating, it hits the ball on the horizontal platform, imparting a horizontal velocity, such that it falls into the open box which is part of the pulley system, thus activating it.

See Saw

- The ball in the view first falls on the left pan of the seesaw, the ball from another field then falls on to the right pan
- This gives an impulse which triggers the upward motion of the ball in the left pan
- After colliding with the parabolic shape, it again falls on to the left pan, thus giving an impulse to the ball in the right pan and trigerring its motion
Lifting mechanism

- The ball, moves on to the horizontal platform and gets trapped between two wings of the rotating paddle
- This forces the ball to rotate along with the paddle, hence trapping it between the wings of the upper paddle
- This lifts the ball on to the higher platform

Spring Mass-Pendulum system

- The pendulum which starts to swing as the simulation starts, disturbs the equilibrium of the spring balls system (the weight of the two balls combined is equal to the spring force at that extension
- The ball on the top gets kicked of by the impulse from the pendulum bob, this gives a net force in upward direction on the ball in the open Box2D
- Both the balls are set into their respective motions now
Actual Implemented Version

This is the screenshot of our simulation at the start of the simulation

This is how it works

The basic objective of the stimulation is to help a passenger and a taxi driver. The driver and the passenger start together and both leave and the driver picks his taxi and then picks up the passenger enroute. We are using a lot of physical objects like pendulum, dominos, circular(nearly) paths, bouyancy effect, fast moving rotators, physical balance system, rectilinear paths, principle of hydraulic machine, pulley system, and a lot of other simple physical principles.
Pendulum And Spring

- The simulation starts with a pendulum disturbing 2 balls which were resting on a spring, where the ball on top (D) represents the taxi driver, and the other ball (P) representing the passenger.
- The pendulum hits the ball on the top and sets it into motion. As D and P were resting on the spring, the unbalanced upward force on P now sets it into motion.
- Thus both the driver D and the passenger P have begun their journey.

Motion of D: Conveyor belt and Pulley System

- The ball D now falls on the conveyor belt and then gets a leftward momentum along with the conveyor belt.
- It falls on to the second conveyor belt and changes its direction of motion to rightwards due to the property of the conveyor belt.
- D then disturbs the hinge, and then falls on to the right element of the pulley system. The disturbed hinge kicks of the heavy ball into the left element of the pulley system.
- This ball being heavy moves downward under gravity and the right element moves upward making a path for our D to move.

Motion of P: Semicircular Tracks and Hydraulic Machine System

- P which was set into motion due to the spring force now sees a series of circular paths in its way.
- It then falls on a hydraulic machine setup’s right piston.
- The increased pressure transmits to the left piston (in fact to every point in the fluid) by Pascal’s Principle.
- So the left piston raises upward due to the increased pressure and the hinge joint gets an impulse.
- This impulse makes the domino on the hinge to fall, leading to a series of collapse of the dominos to the right to hinge.
- They in turn give an impulse to the balls which were put the there.
- These balls now collide with P which fell on to the hydraulic machine. (i.e. P transfers some momentum to the hydraulic machine framework and after some series of steps, the hydraulic machine in turn transfers momentum to P.)
Motion of P: Physical Balance and hinge

- P now sees a physical balance kind of a system and when P falls onto the pan of the physical balance, it settles down, then another ball falls on to the other pan of the balance with a large enough momentum.
- This gives an impulse to P which is in the other pan because of the collision of the left pan with the base under it.
- Now P hits the hinge above it and opens it because of its momentum.
- And before P comes down the hinge closes, so the passenger P now moves on the next path.

Motion of P: Hailstorm Generator

- P now moves on to the circular steep path.
- Then it imparts part of its momentum to the C shaped object.
- With the remaining speed it climbs on the horizontal base.
- Here P gets a kick (impulse) from the rotating motor and then it moves into the series of roads at the right most part of our simulation.
- The disturbed C shaped object now hits the hinge joint, which opens the flow path for the balls inside the box and they fall into the water pool at the bottom as a hail storm.

Driver picks up the passenger

- After travelling through the series of roads, P reaches close to the bottom.
- At nearly the same time the taxi with the driver comes to this place after all the above steps.
- P now gets into the taxi along with the driver D, thus ending a happy simulation.
Deviations and reasons

- The shape of the funnel was in a curvilinear way when proposed. We changed it into a more directed triangular funnel.
- The inclusion of actual liquid material in the hydraulic machine. It was actually unnecessary as the same effect can be achieved in a simpler way. Moreover, liquid particles drastically increase simulation time.
- The cork’s shape was changed from the proposed one in an ergonomistic way so that it avoids collisions with the balls.
- The see-saw system was desirably changed so that larger impulses can be given by incorporating a pad that has a restitution much larger than 1.
- Various walls in the workspace were added to further direct the ball properly.
- Some of the dominos were replaced by perfectly elastic balls so that maximum impulse and energy are transferred.

Profiling

The call graph of the initial code

The call graph, magnified:
Initially we thought of simulating a pool of water using a large number of small spheres. But on getting the profiling data the following functions took too much time.

\begin{align*}
\text{b2World::SolveTOI(b2TimeStep const&) [1]} & \quad - 23.9\% \text{ time} \\
\text{b2Contact::IsEnabled() const [2]} & \quad - 21.7\% \text{ time} \\
\text{b2ContactSolver::SolveVelocityConstraints()} [3] & \quad - 11.5 \% \text{ time}
\end{align*}

All the above functions are taking a lot of time as there are many spheres in the pool implying many contacts and thereby resulting in an exponential number of function calls related to class b2Contact in each time step.
The call graph of the final code optimised

In order to resolve this we simulated water using a static body which on contact with other objects behaves like water. This is achieved by toggling the sensor variables of the body.

After doing that the functions consuming more time are; b2ContactSolver::SolveTOIPositionConstraints(int, int) [1] -13.4% time b2ContactSolver::SolveVelocityConstraints() [2] -12.9% time operator-(b2Vec2 const&, b2Vec2 const&) [3]

The amount of time that was propagated directly from the child into the function for b2World::SolveTOI(b2TimeStep const&) in the first case is 38.93 whereas the same in case of b2ContactSolver::SolveTOIPositionConstraints(int, int) in the second case is 0.60 which is a significant reduction.

The %time of SolvePosition and SolveVelocity constraints is the highest after optimization because of more sensor operations in the timestep function. But the optimization is significant.

Issues faced and solutions we employed to overcome them

- Inclusion of a materialistic hydraulic issues requires larger simulation time. In order to overcome this we visualised the liquid virtually and simulated the forces that are applied by the liquid on the external objects so that other objects actually feel the presence of liquid. Also the quasistatic motion of the piston is ensured by toggling the kinematic functions on b2Body in the iterative step function.

- Similarly, a physical conveyor belt was avoided by toggling the the contact conditions in the time-step function.

- Transfer of momentum due to fall of dominos wasn’t sufficient for the translation of the ball receiving impact. Instead a sequence of perfectly elastic balls was created so that their collision transferred maximum energy.

- The L-shaped object that was proposed was changed to a C-shaped object in order to overcome toppling issues that leads to greater chaos.
Techniques Used in the project which are taught in the course

Presentation of our work
- \LaTeX
- BibTeX
- Beamer

For getting to the outcome of the project
- Box2D
- makefiles
- Terminal used extensively instead of GUI
- git
- gprof

Contributions
- Nikhil Kumar(140050037) - 100%
- Jayanth Shankar(140050039) - 100%
- Uday Kusupati(140050048) - 100%

Honor Code
We hereby pledge on our honour that we didn’t involve in any malpractice and perfectly abided by the rules stated at the start of the course.

References
[2] [3] [4] [1]