IoT + The Fan Experience

18-738 Sports Technology

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The Hockey Puck

- Flat, solid, black disk-shaped objects made of vulcanized rubber
- Regulation National Hockey League (NHL) pucks:
  - Black in color

    Pucks are frozen to reduce the bounce on the ice.
  - 3 in (7.6 cm) in diameter, 1 in (2.54 cm) thick
  - Weigh 5.5-6 oz (154-168 g)
  - Edge has a series of "diamonds," slightly raised bumps or grooves
  - Diamonds give a hockey stick something to grip when the puck is shot
- Each team has a freezer of pucks at all times (frozen to reduce bounce)
  - Team receives a supply of pucks at the beginning of each season
  - Rotated so that the older pucks are used first
  - Pucks are kept frozen in an icepacked cooler on the officials’ bench

The Hockey Puck

The FoxTrax Puck

- 1994 – Fox Sports just acquired the right to produce NHL games
- Motivation
  - Viewers' biggest complaint was not being able to see the puck on TV
  - David Hill, President of Fox Sports
    - "What I'd really like is a system that can track and highlight the hockey puck—but I'm sure that's not possible"

People want to see it in a visually distinctive way.

- February 1995
  - Team assembled to developed the digital/electronic/laser puck
  - New venture called Shoreline Studios
  - Some ex-employees of SGI, employees from Etak (another company that worked with Fox Sports), support from the Vice-President of Product at Fox Sports
  - To debut at the NHL All-Star game , Jan 20, 1996
  - Rick Cavallaro, team lead, says, "We had 11 months to develop a system to track and highlight a frozen hockey puck traveling at times in excess of 100 mph after being walloped by angry 250-pound men with sticks."

Something Old, Something New

- Something new
  - *Puck location:* "Blue glow" to the hockey puck, so a viewer could follow the game without straining to see the puck
  - *Puck being obscured*: Show the puck's location even when it was hidden by players or sticks---an X-ray effect would appear when the puck was hidden by a known object, like a wall

    If we want to see it even when obscured, it should not be line-of-sight.
  - *High-speed pucks*: A comet tail—a graphic to indicate puck speed in excess of a predetermined threshold during slapshots
  - *Puck speed:* A small rectangular graphic in the lower right hand corner of the screen to show a digital readout of the puck speed
- Something old
  - Puck should look, weigh, and respond exactly as always to the players, officials, and fans
  - The system not to be used to judge goals or make official calls, but strictly to improve the production for TV viewers

This is not an officiating tool! It is just to improve the viewer's experience.

How to locate the puck?

How to overlay puck onto the viewer's TV?

What did the viewer see?

https://www.youtube.com/watch?v=grOttsHuuzE

Even when the player obscure the puck, the glow is still available for the audience.

Bluish halo tail on the puck.

Track it in 3D space, a reapter in the puck, radar send a chirp, and compare the frequency signals. Very much like trangulation. But you need to have at least 3 of these.

Design #1: Finding the Puck

RF Reapter Solution Chirp.
5Hz 10 Hz 25Hz... repeated by the RF.

The puck usually has a blue tail, when the speed if high, becomes red tail. The left bottom corner is a speed display.

- Tracking the puck in 3D space
- A radar repeater in the puck , 4 microwave radars (units) around the arena
- Each unit sends a "chirp" (a brief RF signal whose frequency increases rapidly) repeated by the puck
- By comparing the frequency of the outgoing RF signal with that of the repeated RF signal, compute the time it took for the signal to reach the puck and return → compute each unit's distance to the puck.
- Knowing the locations of each of the 4 units and the puck's distance from at least 3 of them → compute the 3D position of the puck

The chip frequency is determinstically increasing.

Each units is sending different sequence. The pucks receives all of these and repeat the chirp frequency it just received back. Use at least three of four redars directed at the ice.

Problem 1: You cannot find the exact location in 3D space -- you need X Y Z
Problem 2: How do you make sure the puck is overlaied on the view of the viewers at home, the halo effect.

Design #1: Overlay on Broadcast Footage

- Okay, so now you have the puck's location
- How do you show this on the actual TV broadcast someone gets at home?
- Need to determine the field of view (FOV) of the broadcast camera(s) to overlay puck on the resulting video
- FOV = pan, tilt, zoom of camera

This means we need to know where the broadcast cameras is pointing. We need to overlay the absolute position onto relative position posed byb the camera.

- Pan and tilt of the camera
  - Mounted an infrared (IR) camera on the lens of each broadcast camera
  - Placed IR beacons (infrared-emitting diodes) in known patterns around the rink
  - Locating the beacons in the IR cameras' FOV

frame of video..

That way we know which direction the broadcast camera is pointing, this gives pan and tilt.

- Zoom of the camera
  - Outfitted the broadcast camera lens with encoders or took analog voltage readouts to determine the zoom

The zoom can be read out from the voltage encoder.

Every camera is now an IR camera.

Microwave radar repeater, the dome start to hum because of resonance.

Hockey Arenas and RF

Lessons Learned

- They built the radar repeater outside and it worked accurately and robustly
- Could also be miniaturized

- They took it inside the San Jose Sharks' arena
  - Realized that the structure of hockey arenas reflects radio waves quite efficiently.
  - Whole building basically started to "hum"
  - Ice attenuated the signal significantly more than expected

    when the puck repeat the signal back the signal is greatly attenuated.
  - Signal-to-noise ratio (SNR) that was unacceptably low
- Scratch, the RF repeating solution!

So, what next?

Relevant Detour: Infrared (IR)

IR is lower frequency than human can interpret.

- Also a replacement for short-range cables
- Using light waves of a lower frequency than the human eye can interpret
- Inexpensive as well, but a couple of drawbacks
- Line-of-sight technology, e.g., point the remote-control at the TV to operate it
- One-to-one technology—only send data between two devices at a time
- However, interference between devices is rare
- Message only goes to the intended recipient (the one-to-one nature of the tech), even in a room full of IR receivers

IR is one to one, one device to another. It is line-of-sight, Interference is rare.
Even there's a room full of IR receiver, it will only go to one.

- Bluetooth—also inexpensive, also replacement for short-range cables—but addresses the limitations of IR systems

Design #2: How about going all IR?

Use IR instead of RF chirp design now.

- Track the puck through IR
- Put IR emitters in the puck
- Expose the IR emitters, but keep them flush to the surface
- Look for the IR emitters in the IR cameras
- But, would the IR emitters take a beating?

It means you need to place IR emitter in the puck.

You need to have IR emitter shine to the surface.

- Another interesting design consideration
  - Why not put retro-reflectors on the puck and then put IR flooding around the arena to find the puck?
  - This meant changing the appearance and surface of the puck
  - Also, some people's clothing (jogging suits, security personnel) might affect the system

Solution, you can change the surface of the puck and make sure it shines IR, place IR camera all around and catch that objects.
There might be a lot fo obects in the arena with reflective tape on it. Security guard with yellowish color.
Interference with flash photography. These would blind the IR camera.

Design #3: Modified radar approach

- Rather than returning a radar signal, embed a free-running RF transmitter within the puck; have units around the arena as before
- Puck-embedded RF transmitter to chirp 30 times per second

When we have "repeaters" in the design 1, we have humming, setup resonance frequency. The resonance cause arena start to humming.

- Significantly improved the SNR because it could run full-tilt at all times

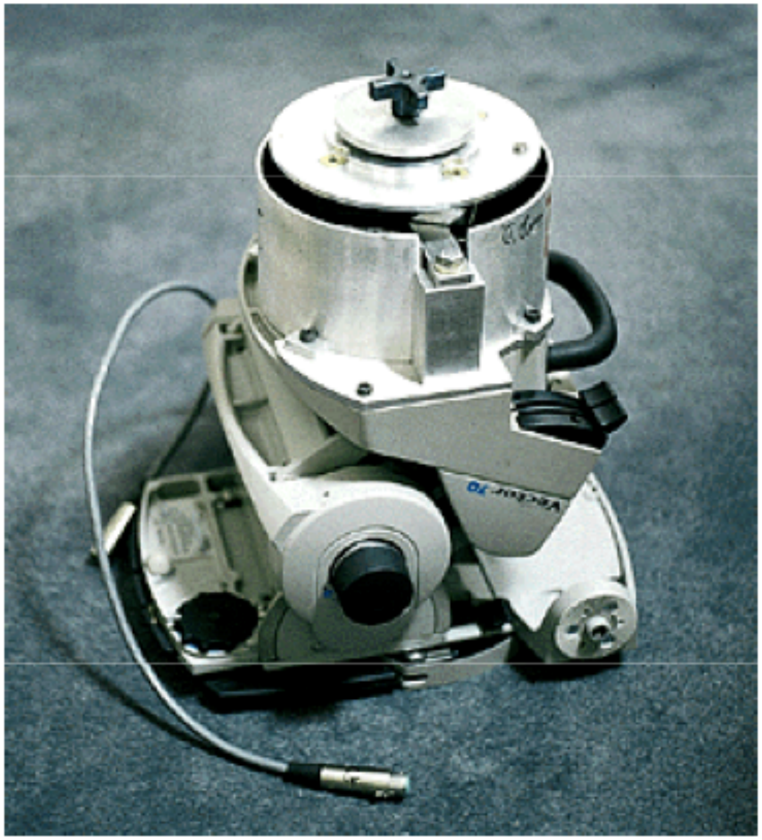
Full-tile, as opposed to in design 1, we need to wait for the repeater.

  - Compared with a repeater, which responds proportionally to incoming signal
- Used significantly less RF and allowed for less expensive radar receivers
  - Reduced FCC concerns
- Unfortunately, only obtained pseudo-range from each unit
  - Could not directly compute the distance from a given unit to the puck, but for any two units, could compute their differential distances to the puck
  - Must have four units with a clear line of sight to the puck at all times (and at significantly different angles from one another)
    - Infeasible -- puck often gets trapped in the corner with a few players
  - Very much like doing GPS inside

Final Solution: Free-running IR emitters

RF Reapter -> IR Alone -> RF without repeater (free-running) -> free running IR Emitters.

- Active IR emitters in the puck IR running emitters all the time.
- Detecting these IR emitters with IR cameras attached to local computers
- Local computers would relay information to more sophisticated computers located in "The Puck Truck"
- To know pan and tilt of broadcast cameras
  - Rigged the broadcast camera tripod heads with optical shaft encoders to report pan and tilt
- To know broadcast camera zoom
  - Analog-to-digital converter (A/D board) in the computer to read the analog voltage describing the current zoom.



The Puck Truck

- Contained a more powerful SGI Indigo II Impact computer
- The Impact computer
  - Synthesized all the incoming data to compute the 3D coordinates of the puck
  - Used the pan, tilt, and zoom data from each broadcast camera to determine where the puck should appear in each video frame
  - Rendered the graphic highlight to be sent to a linear keyer
  - Linear keyer fused the broadcast camera video and the graphic effect to produce the final product that viewers saw at home
- Computations required as many as 5 video frames (1/6 sec)
  - Stored these in a frame buffer while they waited to be combined with the graphic effect
  - Opportunistically grabbed10 frames
  - Allowed placement of the highlight on broadcast video even if the sensors lost the puck for as many as 5 frames
    - Interpolated past puck position once the puck was reacquired

Sync Detection System (1)

Free running = Pulsing IR all the time.

- Puck should be detectable despite the very bright arena lights
  - Basically, the SNR of puck detection should be reduced as far as possible
- Puck sent out pulses in very short bursts

  Puck send pulse and the IR camera shutter synchronize with these pulse.
- IR cameras were synchronized to that pulsing
  - Basically, IR camera shutters were timed to coincide with these pulses
- Why?

  If the IR camera shutter synchronize with the puck pulse is better than IR camera open all the time picking up all the noises.
  - The IR cameras "saw" the puck only while it was pulsing
    - The cameras integrated the background light only over the 1/8,000th of a second during which the puck's pulse was on (and not the remaining time)
  - Improved SNR by as much as 300 times
  - Allowed for batteries to power the puck long enough to be practical
- How?
  - Pulse detectors located around the arena with a narrow-band filter that filtered out all but the specific frequencies of the puck
  - Reported the detected pulses back to a sync computer in the Puck Truck
  - Sync computer triggered the IR cameras to open their shutters

Sync Detection System (2)

- 20 pulse detectors to achieve adequate coverage
  - 10 pulse detectors in the rafters looking down at the ice,
  - 10 mounted on top of the glass around the rink
- Ensured that the puck was always in view of at least one pulse detector within range
- 3 flash detectors
  - Detected the high-power strobe flashes when still photographers took pictures
  - Used to "blind" the sync system briefly to avoid confusing the system and losing sync

- Can track the puck even in very noisy environments even without flash detectors
- Sync system can "coast" for several seconds even when puck is hidden

There are 20 pulse detectors.

They are all seeking the pulse of the puck.
The puck is always in view of a pulse detector.

20 pulse detector + 3 flash detector -> catch the flash strobe from photograph. Every single time if there's flash it can detect.
Let the pylse detector just ignore the flash pulse because that is confusinng.

It is possible if you have high amount of flash photography, the system might be blind.
If the puck is hidden, the system will guess where that is.

IR cameras

- 10 IR cameras mounted rigidly around the arena
  - Resolution of 2-4 inches of ice to one pixel
  - Depending on the location of the IR camera and length of lens used (6.5mm, 8mm, 12mm, and 16mm lenses depending on IR camera placement and coverage)
- IR cameras also had the narrow-band optical filter to filter out all irrelevant frequencies
- Temporal filtering method to improve SNR
- How? Capture 2 frames of IR data every 30th of a second
  - One during a puck pulse, and one immediately after
  - Only difference in the two frames is the presence of the puck
  - Frames taken so close together that the background should match, and when subtracted, should cancel out

Pulse detector synchronized with same frequency of the puck.

In the first frame, you see the puck, because it is pulsing.
In the next frame, you don't see because the pulse finished.
The background should match, and then substraction should allow us to know where the flash is.

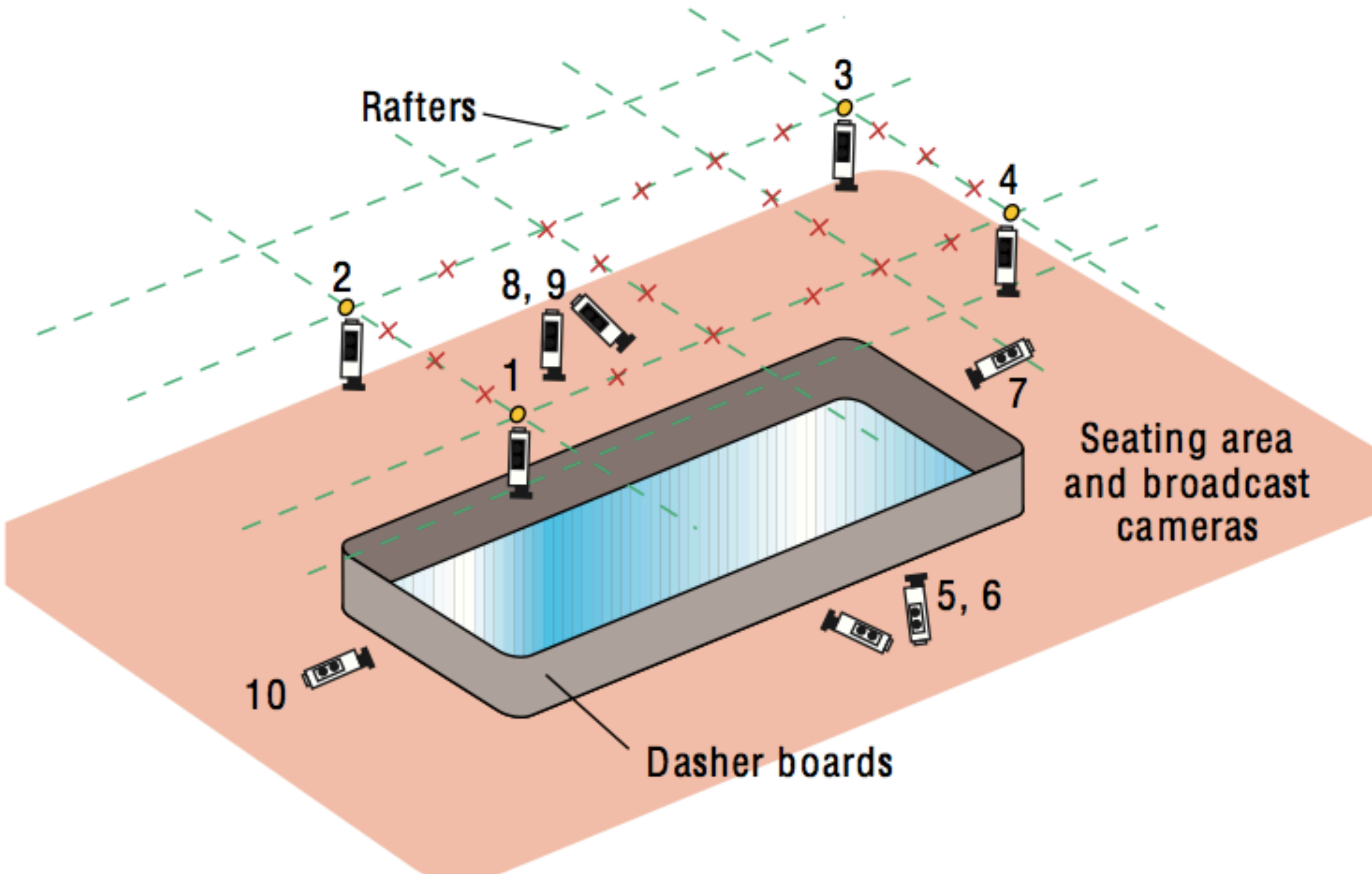
IT infrastructure

- 10 PCs associated with the IR cameras, 2 PCs for the sync system
- Collocated IR camera computers are industrial rack-mount, 66-MHz, 486 PCs in road cases
- PCs collect the IR and pan-tilt-zoom data to send to Impact computer in the Puck Truck

Flash detector look for flash photography.
In the broadcast camera, the optical shft encoder looking for pan and tilt, and ADC convector get the zoom.

- PC software
  - Finds “clusters” of bright pixels and sends this information rather than reporting on individual pixels from the IR camera
    - Collocated up-front video processing reduces the bandwidth requirements and distributes computational load,
    - ~~Avoids the Impact computer from having to perform this function for each IR camera~~
  - Watchdog timer boards in each PC to auto reboot and restart software if hung
- Communication back from PCs
  - “Good old copper wiring” (twisted pair RS-422)
  - “Spent more time debugging wiring problems than any other single issue”

Final deployment



As for the puck itself

- Requirements
  - Emit the necessary IR signature, stand up to the beating
  - Look and perform exactly like the NHL-approved pucks
  - Retain puck's size, weight, balance, rebound, and coefficient of friction
- Interesting quirks
  - Team did not originally realize that pucks were frozen ahead of time
  - Puck must exhibit the same rebound as an NHL puck both frozen and at room temperature (and yes, the players can tell)
- From the electronics viewpoint

  Pucks can be as fast as 70 mph.
  - Must withstand tremendous accelerations and compression loads
  - Must perform satisfactorily at low temperatures. The pucks need to be frozen for period of time before game.
    - Since batteries lose both capacity and current capability at low temperatures
  - Must be rugged, i.e., pucks should split apart and spew electronic components on a good slapshot
- Find an adhesive with the proper weight and flexibility—and that would NOT let go!

Electronic Puck

- Standard NHL puck was cut in half

And put it back.

- Miniature circuit board and a battery placed inside
- Circuit board contained
  - Shock sensor

    It won't use battery when puck is not being played.

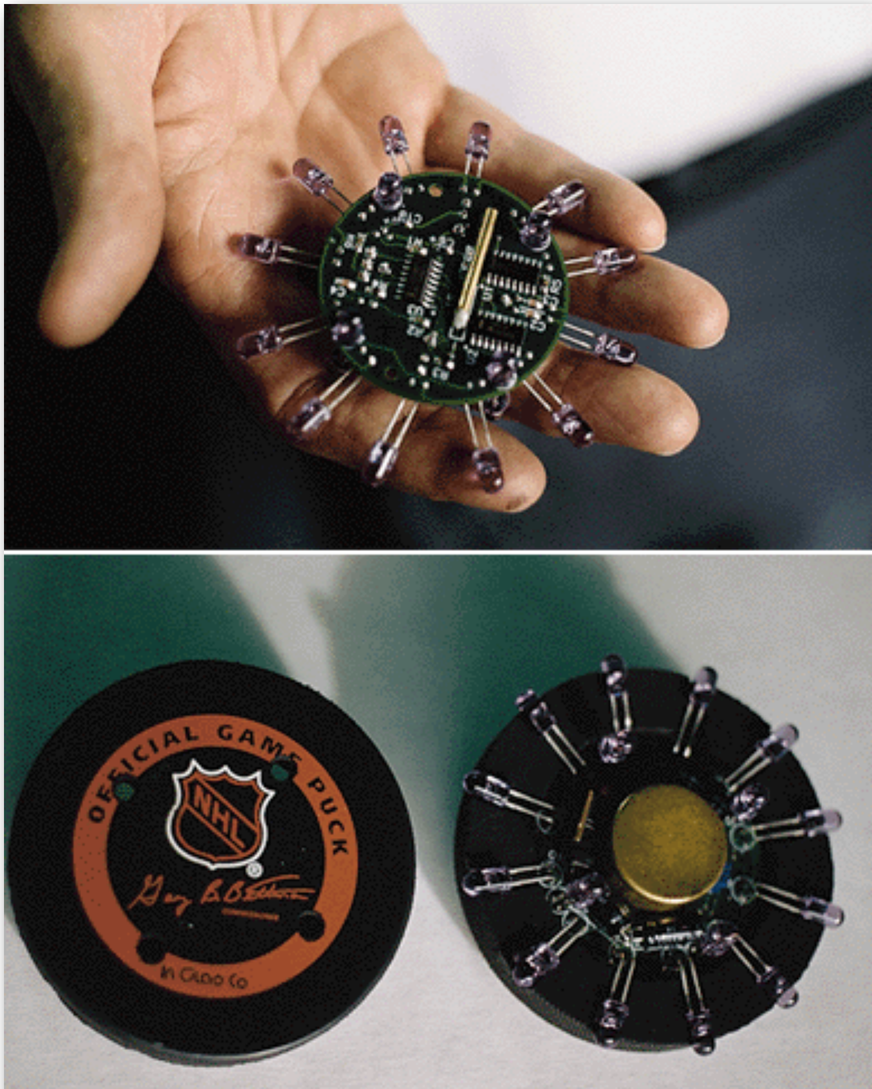
  - IR emitters that protruded slightly out of the puck's flat surfaces as well as the circumference of the puck
- 20 IR emitting diodes (IREDs)
  - Five strings of 4 IREDS
  - 4 on top, 4 on the bottom, and 12 around puck circumference
- Puck turns on with an internal shock sensor
  - Remains on for 45 seconds from the most recent shock

    Sometimes goes to the audience. You don't want to have the battery to drain.

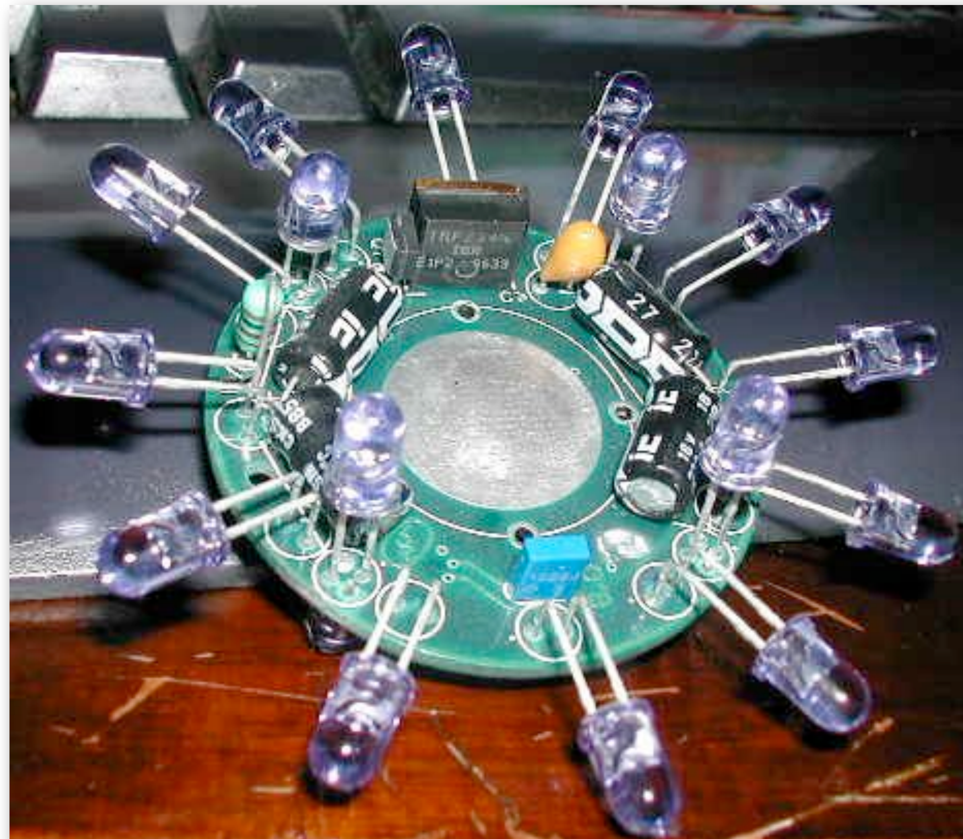
- Resulting puck had the same weight, balance, and rebound as original puck
- Two halves were sealed with a proprietary epoxy

Make sure that the sport is the same.

Final packaged product



Purple things = IR diodes.



The Puck Truck

- 40-foot "semi"
- Wired to the arena to collect all the necessary data
- Wired to Fox's production truck to receive the video signal and information about which broadcast camera or replay deck is on the air

Up-front calibration of the system

- Must know the location of each IR camera, the broadcast cameras, and the dasher boards that surround the ice
  - First established a 3D coordinate system in the arena
    - Origin of this system is placed on the center face-off circle with the *X* and *Y* axes on the ice and the *Z* axis pointing straight up
- Drill 9 small holes in the ice and filled them with freezing ice paint

  They created a fake physical coordinate system. And they try to look at these from lens. Hawkeye did a lot of calibration.
  - Measured the distance between each of these marks and from several of these marks to the dasher boards with a laser range finder
  - Established the rink's dimensions and coordinate system relative to the rink
  - Placed an active puck on each mark at a time while taking note of its image in each of the IR cameras
  - Computed the position and orientation of each IR camera.
- Found and marked the optical axis of each broadcast camera (in 1X and 2X mode), point it at each ice mark, and solve for its location
- Calibrated the narrow-pass filters to eliminate spurious local IR interference
- Calibration took 3 hours, wiring the arena took 2 long days

Fear, adrenalin, no sleep

The system was finally "ready for prime time"—or so we thought. We had performed three demos for Fox Sports executives at various stages of development. Despite many long nights and a well-founded fear of failed demos while living in the rafters at the San Jose Arena, our final demo in San Jose was a genuine success.

Next we would experience fear and loathing in New Jersey: The electronic puck was scheduled for its first official NHL game (though the effect was not to be aired) when we learned that the real world is truly a cruel place. We had hoped to do arena surveys during development, but simply did not have the time. Now we found the east coast shut down by the biggest snowstorm in anyone's memory and could not get ourselves or the trucks to the Continental Arena in N.J.

When we finally arrived, we wished we hadn't. The entire development team put in a 24-hour shift culminating in a live demo that did not go well. Even during the game, we were modifying software and hardware to try and salvage the system. By the end of the event—when all we could track was a Zamboni—we realized that the IR environment at the Continental Arena (like some of the other older arenas) was truly hateful to our system.

We packed up and escaped like thieves in the night, headed for the much newer Boston Fleet Center, where the system was to debut in one week during the NHL All-Star game. While the environment was generally much better in Boston, we had not anticipated everything from laser lights to fireworks. Nevertheless, with some delicate conditioning we had the system up and running with two days of margin before the game. David Hill used this time to call a press conference where the system was demonstrated publicly for the first time. The resulting national coverage over the next three days was breathtaking. Two days after the system operated successfully at the press conference, it performed well at the All-Star game—and everyone exhaled.

[Rick Cavallaro, CTO, Sports Vision]

End-result

The purple ring on the puck: https://www.youtube.com/watch?v=grOttsHuuzE

Public reaction

- New fans enjoyed it since they could follow the game more easily
- A Fox Sports survey found that 7 out of 10 respondents liked the new puck
- On the other hand, hockey purists hated it
  - Argued that the video graphics were a distraction and turned hockey into a video game
  - Claimed it really should not be that hard to see a black puck on white ice
- Pucks were too pricey and not available to players for practice
- Sportswriter Greg Wyshynski (Puck Daddy of Yahoo! Sports) called it the second-worst idea in North American sports history in his book *Glow Pucks and Ten-Cent Beer*
- Not used any more today

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