BALL TRACKING PERFORMANCE
World cup ADIDAS/Kinexon ball versus Pulse ball

https://fivethirtyeight.com/features/the-world-cups-new-high-tech-ball-will-change-soccer-forever/
..."With KINEXON's ball-tracking system, that data is coming in at **500Hz,** meaning any gaps in true positioning are below two milliseconds long – or 10 times shorter than standard 50Hz tags."...

Pulse ball-tracking system, that data is coming in at **1000Hz**.
twice as fast, for accurate event detection and true 3D positioning

Summary: The Pulse ball system exceeds the world-cup 2022 ball specifications.[(5)]

System performance & specifications				
		Pulse	**Adidas** World-Cup	Kinexon
Sensor placement	Center or Valve	**Center**	**Center**	**In Air-valve**
Sensor weight	gram, lower is better	**2**	**14**	**15**
Ball OEM	Producer	In-house, Jalandhar	Adidas, Yayork plastics	Select
Battery capacity	mAh, higher is better	**500**	110	110
Motion Sensor		ICM42686	ICM20649	ICM20649
Accelerometer, Gyro	bits, higher is better	18, 19	16,16	16,16
Accelerometer, Gyro	Max update rate Hz	8000, 8000	9000, 4500	9000, 4500
Acceleration Range	G, higher is better	0..32	0..30	0..30
Full range resolution	mG / bit, lower is better	0.24	1	1
Gyro Range	degree/sec	±4000	±4000	±4000
Tracking chip, UWB	**U**ltra **W**ide **B**and	DW1000	DW1000	DW1000
2nd communication chip	Bluetooth 5.3	**v**	**x**	**x**
Pressure sensor	+- 0.025 bar resolution	**v**	**x**	**x**
Tracking firmware	Sensor OEM	In-house	Kinexon	Kinexon
Ball Position [(1)]	Updates/sec	**150**[(1)]	**50**	**50**
Ball 2D Accuracy	cm, lower is better	**5**[(2)]	**10**	**17**[(2)]
Ball range (see page 5)	m, higher is better	**220**	**100**	**100**
LPS Capacity	Locates/sec/channel	**2800**	**2000**	**2000**
Motion Sensor	sample rate Hz	1000	500	200
Impact detection [(3)]	resolution	**1ms**[(3)]	**2ms**	**5ms**
System latency [(4)]	Lower is better	**160ms**	250ms	250ms

1) 150Hz ball position tracking. Default is 50Hz. Maximum is 1000Hz/ball, using the standard system configuration.
2) Kinexon 2D ball position accuracy verified by **Fraunhofer +-17cm** and **FiFa +-20cm**. Adidas/kinexon world-cup ball has the sensor placed at the center, improving the average accuracy to +-10cm. The Pulse ball has a further improved accuracy due to a lower measurement noise level (see page 4). Verified using a tracked 480fps high resolution camera.
3) For ball kick detection, the time of detection of a kick is very short, about 5ms. In the pulse ball system, impacts are monitored a 1000 times per second. Based on the sensor data, sampled at 8000 times/second. By default motion data is captured 200 times per second for players. All data is offloaded to a network-PC or phone,12.5 times per second with an 80ms latency (delay). 3D visuals show after 160ms. Motion data contains: X Y Z-axis for gyroscope, accelerometer and magnetometer + the moment of impact during this 80ms measurement period with 1ms resolution.
4) ***Latency means:*** The average time to get the 3D position data processed in the PC and displayed. Mentioned latency data is FiFa or 3th party verified. Broadcast level latency, for information augmentation, for televised events, like the Olympics, needs to be sub 200ms.

For off-side and other ball kick detections, the kick event itself happens in 4 to 8ms (milliseconds):
The ball accelerates from 0 up to ..140kmph within 8ms.
The acceleration is about 3000G for a few milliseconds.
Modern sensors register up to 32G and use dampening to measure.
Earth gravity, for comparison, is only 1G.
Overview of OEM's at: hightecinsport

ADIDAS Ball Patent for a center mounted sensor

US 7740551

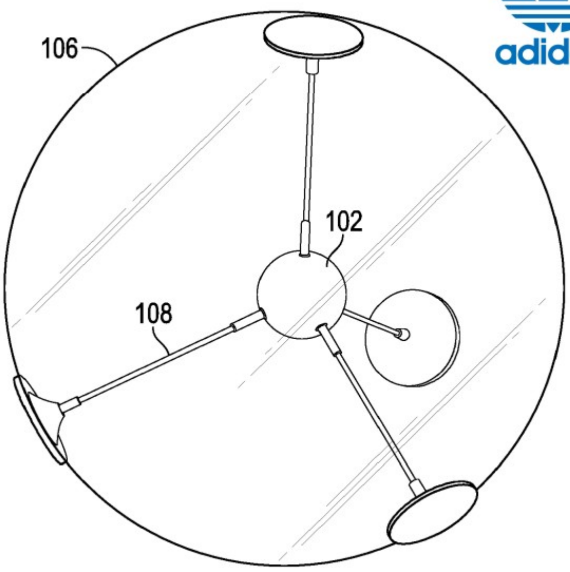


FIG. 2

See also ADIDAS patent US 7740551.pdf
1) A bladder in accordance with the invention can include at least two lines of intersection, wherein the lines of intersection define an angle of about 120 degrees. In one embodiment, the points at which the lines of intersection contact an outer surface of the bladder define a substantially regular tetrahedron.
2) In contrast to the prior art discussed, the electronic device is positioned by elements that can transmit more than only pulling forces. When the electronic device is deflected from its predetermined position, the planar reinforcing Surfaces provide additional shearing forces. Furthermore, they dampen, similar to an oil pressure bumper, an arising oscillation of the device, since any movement of the reinforcing surfaces causes a shift of the air volumes inside the bladder.

***Comments**: The elements going to the center sensor can push and pull to keep the sensor at the center. Even under heavy deformation as caused by a kick. **See video: Ball_impact.mp4** The kick duration is about 5ms to reach top speed. In order to measure the moment of a kick accurately, a sample rate higher then once per 5ms is required. Typically 2x higher (400Hz) This results in a lot of data per second. Sensors mounted on the center (not on the valve) are preferable for professional games.*
So far only the Adidas ball and Pulse match balls have the sensor mounted at the center and survive the brutal kicks by professional players.

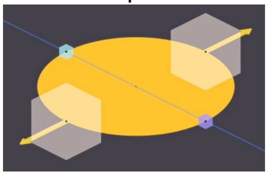
One of the differences between the pulse ball and Adidas/Kinexon is the internal structure and properties thereof. In order to measure the force of the kick, the Adidas method requires the sensor to sample 400+ times/sec. 500Hz is then needed to avoid missing the event and to have enough samples to determine the kick force.
The issue here is the acceleration itself (3000G) exceeds the limit of the ICM20649 sensor used by Kinexon even with shock dampening measures. The acceleration of the ball can easily reach 3000G which is impactful for electronics to handle. In case of direct measurement, sensors can measure up to 30G and handle up to 10000G.

The pulse ball sensor structure works of a different physics principle.
Which does NOT require such a high sample rate to measure the force of a kick.
This different approach also avoids patent infringement with Adidas.
The limited amount of physical methods to mount sensors at the center prevents competition from entering as well. Some OEM's (Gengee, Sportable, Shottracker and Kinexon-Select) therefore choose to mount the sensor at the valve. A sensor at the valve makes **G**oal **L**ine **T**echnology-detection difficult for obvious reasons.
It is better to have the sensor at the center of the ball for such measurements like GLT.

Below 10cm from the ground the range of the tracking sensor is reduced by about 70% (RF 'ground effect')
Valve mounted tracking sensors places the sensor almost at ground level, depending on the ball orientation.
Center mounted tracking sensors are always about 10+ cm from the ground.
With a placement of 70 cm or higher from the ground, the max range is less affected
For stadium systems the max range of the Pulse ball LPS system is approx 800m using special antennas

Sensor Mounting

Mounting the sensor at the valve upsets the balance of the ball. It may seem trivial to offset this unbalance, by placing a counter weight, on the opposite side of the ball. The problem with such an approach is it produces wobble in the flight path of the ball. Because of the Dzhanibekov effect.



For Dzhanibekov effect see video: *Dzhanibekov.mp4* *(c) veritasium*

Such wobble is similar to the infamous Jabulani ball which had an irregular flight path. Mainly caused by the irregular pattern of the grooves/seems of the Jabulani.

See also: ***Comparison_Jabulani_Brazuca_non-spin_aerodynamics.pdf***

The key is to have the lowest sensor weight, to not disturb the flight path of the ball.

The most even, and regular pattern of seems on the ball surface, provide the most predictable flight behaviour. Both for slow and high ball speeds. At speeds above 20m/s laminar airflow over the ball changes to turbulent flow. Since air-friction is constantly slowing down the ball speed, one can create the famous knuckle balls.Knuckle balls are shots without any ball spin, but with a changing flight pattern mid-air while going fast, then slower. Passing the laminar flow speeds. The classic hexagon, pentagon surface is still the best for 'even spread air grip' of the ball.

One motivation to create tracked sport balls in the first place is to measure all the relevant properties of free kicks, penalties etc, to quantify which player has 'the best shots'.Not only fast, but also consistent in accuracy, spin and curved flights (magnus-effect) ***video:*** Magnus.mp4 It is not possible for humans to judge the curve effect accurately. Other than forming an 'opinion' from the viewers perspective of that players shots.
Likewise, judging if all balls entered the goal at 'the same place' is too difficult for humans, including the coach.
To solve these issues and bring an easy to use toolset, to the market for training and matches is rewarding.
A new technology wave is arriving in football. ONE set of equipment, replaces stopwatches, laser-guns, sprint gates, cumbersome manual sprint setups, automatic registration, replay in 3D from any perspective, tracking of progress in performance, monitor health, and indicate human body load.
All in one dashboard. All with one mobile toolset.

example
see replay in 3D: ***video goal shot, penalty style:*** Outdoor_16m_3D.mp4

Note the anchor on the left side of the goal which blinks upon the ball passing the goal line within 100ms.
Reaction time of the system is within a fraction of a second.
The system receives the distance measurements, converting it into a 3D positions (200 positions per second).
Then determines how far 'of center' the ball landed.
Then send the instruction to blink the correct (left) anchor into the network.
1 blink means the ball landed 1 segment (slightly) left of the center.
Direct optical performance feedback for the player per shot which is also unique and new in football

Human body motion capture and injury prevention

For full motion analysis, the data stream should be continuous. It is possible to compress the answer into a shorter data format using quaternion notation on the tag itself. This however has the problem of sensor drift. Specifically for the gyroscope which measures rotation. A gyroscope always reports some rotation even if it is idle due to offsets and because the earth is round and rotates. The best way is to forward the raw, unprocessed motion data (gyro, accelerometer, and magnetometer) to the network. Combine this data with the UWB 3D position data. Then use an advanced mathematical method to correct the drift automatically. This method improves the position accuracy from UWB from sub 5cm to sub 2 cm for 68% of all measurements. For injury prevention and real-time human body load monitoring (knee and muscles) 200Hz IMU motion capture is adequate. 200Hz mocap is also the norm for medical grade analysis of human motion.

Tracking system performance

The key performance metrics of any tracking system is **capacity, range and accuracy.**
Pulse ball LPS system capacity: max 2800 locates/sec/channel. Kinexon: 2000 locates/sec/ch
That means to track 2 balls at 150Hz, 350 locates/sec are required.
The rest of the system capacity is than used for player tracking.
The remaining 2450 locates/sec to be used for tracking 98 players at 25Hz for both training and match-days.

How about a tournament
4 adjacent fields, 8 teams 11 players, 4 referees and 4 balls. (88+4) x 25Hz +(4 x 50Hz) = 2500 locates/sec.
The pulse ball tracking system can deploy 2 UWB channels at the same time to track 8 adjacent fields.
A key point is to be able to deploy for many fields with players & balls for different sportfields at 1 location.
Many sports parks have different fields for different sports, close to each other.

Accuracy and ball speed

During the selection of the athlete tracking system for the RIO summer Olympics by Swiss Timing:
Kinexon ended up 2nd and Quuppa 3th. The reason to win, with the 1st generation tracking system was the tracking range of 700+m for the stadium system and it's accuracy.
In the new 2nd generation system, 2023 launch, accuracy and position stability are further improved.

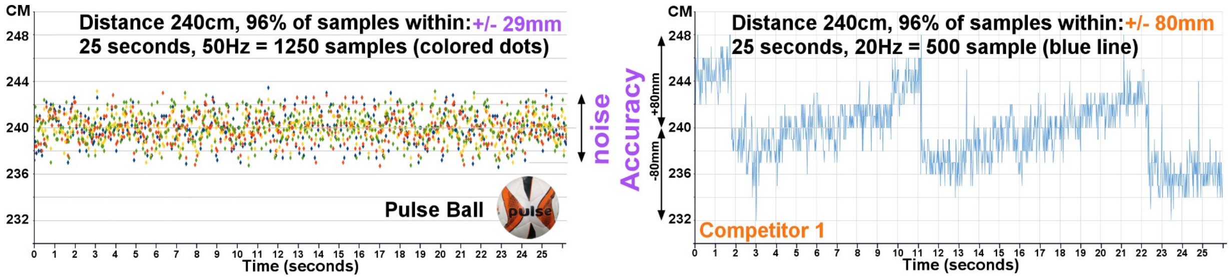


Figure 4: The distances measured with the pulse ball system have +/- 29mm 'noise' independent of the distance.
A special electronics method is used to keep the distance measurement stable over time (left picture).
Without this method you get the more 'wild' pattern in the right picture, also a 240cm average distance.

A new algorithm is developed to determine 2D and 3D positions as smooth as possible in 3D for any kind of object and motion. Slow speed, high speed, wild behaviour and impulses: like a ball bouncing from a wall are handled by one single algorithm. NO need to pre-select a type of filter for a specific use case. Thus reducing the requirement for any user intervention in selecting filter settings for example.
3D visualisation is also very revealing for any 'unnatural' looking motion. So accuracy and motion smoothness is important in visualisation and tracking in general.

Validation
A good way to validate tracking systems is by moving the tag around in circles and increase the speed.
When multiple positions are averaged as a method to improve accuracy this becomes clearly visible.
The circle get smaller and smaller in diameter as the speed increases. Even when the measurements themselves are more or less correct. Averaging introduces position errors, while it was intended to improve accuracy.

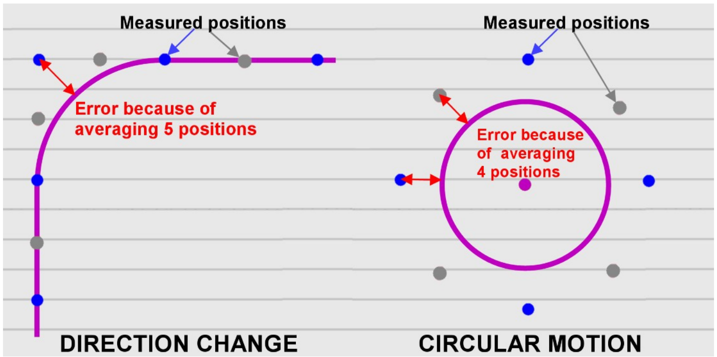


Figure 5: When averaging all samples recorded for circular motion it ends up as a dot at the center.
The same effect for a person running, which performs a sudden right turn in the corner.
With averaging, positions (blue and grey dots): the corner will be 'cut short' in the visualisation.
Increasing the amount of samples per second does improve a bit. Most OEM's use (flawed) averaging.
The new algorithm in the system does **not** cut corners and also does not use averaging.

In the FiFa report on the Kinexon system accuracy decreases with increased speed. This is a clear sign of using averaging to improve accuracy, ***see report*** EPTS_FIFA Quality_Report_Kinexon.pdf, page 4 where performance for objects travelling at speed is less accurate.

The novel algorithm, in use also for the pulse ball, does not show this behaviour and the circle remains the same diameter when the tag increases in speed. This is one of the elements of the solutions which makes it hard to copy for third parties. Positions filters which cancel out noise and/or spikes have a near infinite step response and are complex to tune to the tracked object behaviour. The novel algorithm solves this in an elegant way for all types of motion and tracking removing the need to customize it, depending on the type of motion, of the object.
There are no ready made solutions for sale on the market for these topics. Independent of the amount of available funds, it is not possible to clone or copy such system by 3th parties, new to the market.
Development of a match quality ball for professional use takes about 6+ years. Kinexon released a first version in oct 2017. The pulse ball tracking technology was first introduced for rugby in mai '17 for the televised rugby finals at Twickenham stadium. The Pulse ball qualified for volume production in Q4 '22. Kinexon market release is expected in summer 2023.

APPENDIX

Electronics

The electronics part of the tag inside the ball.
Sensor weight 2.8 gram (coin diameter about 25mm)
Maximum current production capacity 5000 units/day.

Specifications:
- UWB transceiver for tracking and data-link at 6.8Mbps
- Bluetooth 5.3, 8dBm 2Mbps transceiver
- 2 battery chargers
- Motion capture, magnetometer and pressure sensor
- World first **dual** core processor in a LPS tracking system

Cortex M33
dual core 128MHz
1MB flash drive
2x256kB + 64kB RAM

KINEXON: side mounted sensor ('select' ball)

Sensor weight ~15 gram

PULSE vs. ADIDAS/Kinexon : center mounted sensor boards

125mAh/hour of operation	2 x 250mAh	v	Battery	1 x 110mAh	higher is better
Motion capture: speedchange	**18**bit, max 8kHz	v	Accelerometer	**16**bit, max 9kHz	typically sampled at 1kHz
Motion capture: rotation	**19**bit, max 8kHz	v	Gyro	**16**bit, max 4kHz	typically sampled at 1kHz
Range increase ~12m/dB	strip-line, +3.9dBi	v	UWB Antenna	ceramic, +0.7dBi	higher is better
Range increase ~12m/dB	+3.1dB added link budget	v	UWB LNA	x	Low Noise pre-Amplifier
Range increase ~12m/dB	+3dB added TX link budget, 128	v	UWB Preamble	256	transmitted symbols to lock-on
Max range	220m	v	UWB Range	100m	higher is better
TCXO=Temperature controlled Crystal	TCXO 0.5ppm	v	Timing accuracy	Crystal 10ppm	lower is better for fast lock-on
Ball pressure	0... 3 bar 0.025 steps	v	Pressure sensor	x	
Ball status reporting	Bluetooth 5.2	v	Bluetooth	x	
Motion capture: absolute heading	Magnetometer, 16 bit	v	Magnetometer	x	
Charging method 	Magnetic USB-C cable *blink pattern indicates charge-rate*		Charging	v Wireless Qi charge cradle	

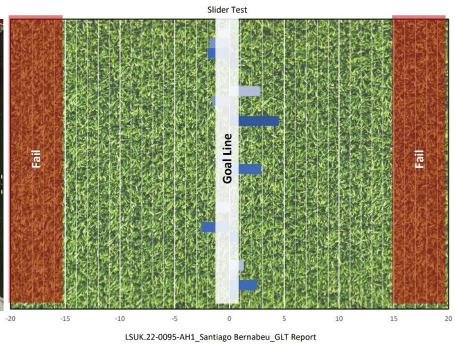
3D replay of a shot on goal + analysis

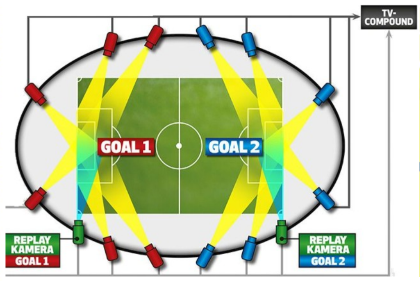
Details of a recorded shot on the goal:
Low **speed**: 8.4ms over 4.1meter distance.
Ball spin: 5.2 revolution per second, 316 rpm (rev/min)
Height, when passing the goal line: 1 meter 17
(represented by a blue dot in the goal area in the 3D render)
Curve (due to magnus effect): 4% of the shot distance.
Feedback
The 100 Watt RGB LED-panels in the anchors, placed on the field, blink a performance feedback pattern.
In this case, the 'pulse' ball missed the target area of the goal by 2.92 meter relative to the right lower side (RL).
The target area for penalty shoot practise is on the left and right side of the goal. Indicated in light blue.
The LED pattern gives direct feedback in about 0.1 second after the ball passed the goal line.
The FiFa time limit for Goal Line Detection is 1 second. 70 cm after the goal line a brick wall was hit and the ball reflects off the wall. The sharp pointy turnaround shows the 3D position sample rate is high (here 200Hz).
The software renders a 'real goal' to indicate where to aim even if there is no real-world goal on the field itself.
2 Anchors placed 7.4m apart 'create a real goal' on the grass field or indoor.

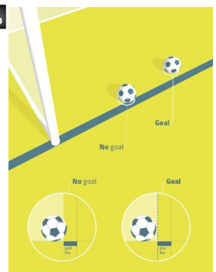
GOAL LINE DETECTION (GLT) using UWB tracking versus Hawkeye

Conclusion UWB system performance:
- Goal detection time to notify the referee is within 0.1 sec (FiFa GLT-specification states within < 1 sec)
- Smoothed 3D flight path accuracy of the ball with UWB is <5cm, similar to optical Hawkeye,Tracab 'prediction'
- Time of flight of the ball is within 0.25ms accuracy. Better compared to Hawkeye 2ms
- Accuracy of Goal Line single position-sample: within 5cm x,y @ 1cpk, this is outside the FiFa spec of 15mm. When using averaging on the slow moving ball this is likely to be within 15mm.. but averaging does not reflect real-world conditions. There is also an issue with the FiFa 15mm specification in relation with the real-world performance of Hawkeye and similar systems like Tracab. End user experience and FiFa committee members rate the Hawkeye system at about 10cm accurate, 95% of the time. This confirms third party field trial results of 8cm to 20cm accuracy as well as news articles on field mishaps.

The FiFa 15mm accuracy specification issue:
The FIFA GLT TEST 07 (slider)Slider test (E01 to E04) moves the ball very slowly with a camera at close range.
All camera's suffer from the same effect that accuracy drops when distance increases.
From a 2022 FiFa accredited test shown below the error is indeed a few mm in the 'ball slider test' (see below).







The FiFa test manual point out the use of a 2000 fps camera (fps = frames per second). Where the camera is placed on the goal line a few meters away from the ball. Also 1.5mm per pixel resolution for the recorded area is required. These 2 requirements are **not** met in the real world stadium setup. This can be considered misleading to continue to claim the GLT camera technology as implemented in the stadium is also mm accurate. As per above FiFa measurement: 1.5mm/pixel leads to 5mm of error. Expect 80mm or error with 24mm/pixel for field deployments. Plus additional errors because of a low sample rate for high speed objects and some other factors. Cameras placed at a distance can zoom onto the goal using a lens. Zooming causes the light intensity for the camera sensor to drop significantly. High speed cameras have a short exposure time. Requiring extra light, which is not available when zoomed in. The stadium floodlights do not create an extra high light intensity around the goal area. Considering the extreme light intensity required for high speed (1000+ fps) at 70meter distance this would appear awkward in the stadium. Visitors would also need eye protection. In practice one can not use high speed cameras at a 50 meter distance in an outdoor stadium at dusk. The same Teledyne 40 tot 60 fps 2k Sony sensor cameras are used both the Sony Hawkeye and ChyronHego Tracab systems. Improvements in light sensitivity from the used Sony sensors go by a few percent per year. No 'revolution' is expected any time soon in this field.

A comprehensive list of 4 ‘field’ errors for camera tracking systems:

1 Samples required for 3D trajectory [error estimation: 10mm to 100mm]
The camera can not be zoomed in too much on the goal area because else, the 3D ball trajectory can not be captured. The sample rate can not be set too high because of low light (exposure) conditions.
Hawkeye is set to 40fps. Meaning 25ms per frame. A ball travels at speeds up to 30+ mm/ms.
Every frame yields a ball position at 750mm intervals.
In cheaper optical tracking systems, rolling shutters cameras are used, instead of global shutter cameras. Global shutter makes an ‘instant’ snapshot, instead of scanning line per line which smears out the ball. Making it look more like a rugby ball at high speeds. Global shutter, high-speed, cameras are significantly more expensive which would drive up the already considerable system price.
To claim mm accuracy, when one only knows where the ball is every 0.75 meter, without ‘distance’ information is a stretch. Within the 750mm ‘measurement gap’. the ball can also hit the crossbar for example, and change direction Throwing the ‘prediction of course’. Multiple camera angles are mandatory. Using 6 cameras per goal as in the hawkeye GLT solution. Of which, 2 are near the goal and 4 are some 40 to 70 meter away. Some of which can have a blocked view by the defending keeper. Some have per definition an unfavourable viewing angle to see the ball passing by. The cameras behind the goal are a bit useless when the keeper catch the ball and falls or walks backward after the ‘catch’. Recognizing the ball from a distance with keepers arm’s around it is a challenge for any camera setup, in a stadium, from a distance.

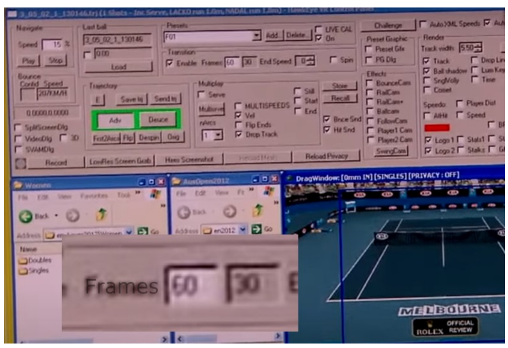
Snow simulation FiFA GLT test (G02): “unroll the short linen inside the goal” is the simulated way to mimic snow. Camera’s at 70meter distance have the snow in front of the lens blocking the view. The ‘snow’ in the goal is not very critical. The ‘snow’ test criteria has ‘room for improvement’.
Also players can block the view of the camera. Radio signals, like UWB, go in part around the players. Meaning obscuring the ball from the antenna by placing your hand about 30 cm in front of the antenna does not significantly effect the ranging result. Blocking in a similar way a camera, will take that camera out of action, leaving less cameras to use.

2 Camera resolution at a distance [error estimation: 25mm]
In order to determine the 3D ball trajectory, at least 10 samples are needed (15 according to Hawkeye operator Matt Allen).
With the goal inside the camera view and a ball travelling at 30m/s this requires a ‘scene cut-out area’ of 45 meter.
To meet the criteria of 1.5mm per pixel this means a 675 Mega pixel camera is required. A 675MP, 2000fps, low light camera does not yet exist. On site Hawkeye camera settings for GLT are HD1900x1080 resolution at **40**fps. See hawkeye software-setting in the image.

For a 45m target area this means 24mm resolution per pixel.
This is far from the FiFa 1.5mm/pixel required for a few mm accuracy.
The 22cm diameter ball shows up as 9 dots across in the frame.
With hawkeye the ball position is known every 75 cm +/-80mm 1cpk (40fps, ball speed 30m/s)
For UWB the pulse ball position is known every 17 cm +/-29mm 1cpk (150Hz, ball speed 30m/s)
As a ‘real-world’ comparison: the Hawkeye GLT and UWB LPS ball tracking have similar accuracy (< 10cm)
UWB LPS has the advantage of 1ms sampling of kick detection and no issues with low light, direct sunlight or snow up to the level where the match will be cancelled. Also the ball position is known in much smaller steps which is relevant when the ball bounce inside the goal from the crossbar. This is a sudden change of direction.
Using the ‘Hawkeye-rule’ for 15 positions to construct a reliable 3D path.
This means the ball will need to travel 15 x75cm =11.25 meter. While the height of the crossbar is only 2.4m.
The chance to have a video frame where the ball is exactly touching the ground is low. Worse case the ball is 35cm from the ground, captured in 1 frame. The next frame 25ms later the ball bounced up and is again 35cm from the ground. The frame where the ball is on the ground does not exist and need to be guessed. When the moment of hitting the ground is known this would be helpful to improve Hawkeye accuracy.
Having a motion sensor in the (pulse) ball, sampling at 1000 times per second, solves that problem.

Likewise: the main reason why replay of a ‘challenged ball’ in tennis is only shown as a 3D-animation. Not the real video frames, which do not show any ball near or ‘on‘ the line.

Hawkeye camera settings in software version 3.5 for line detection in tennis, **60**fps. Served tennis ball speed: 50m/s, 180kph
1 position per 83 cm of ball travel.
Same issue: do not expect mm accuracy with such a setup.



Tracab gen 5 uses : Teledyne DALSA Genie Nano camera with a 1936 x 1216 resolution with up to 30 fps.
Sony Pregius global shutter CCD’s are used in the Teledyne Genie Nano

Teledyne DALSA Genie Nano camera

Hawkeye Teledyne DALSA series. Tennis: 60 fps, GLT: 40 fps

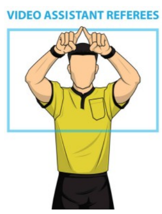
	sensor	Teledyne DALSA	Camera	Frames/ second	Camera without lens	Football GLT
Hawk-Eye	IMX174 2MP	Genie Nano	HD1900x1080	40	€1200	v
Tracab gen 4	IMX174 2MP	Genie Nano	HD1900x1080	25	€800	v
Tracab gen 5	IMX252 3MP	Genie Nano 5GigE	HD1920x1200	30	€1700	v

3 Camera sync and parallax [error estimation: 3mm to 30mm]
Also camera image synchronisation need to be much better then 0.1 ms (hudl sports model) . Since the used camera’s are not synchronized in hardware with each other, but in software via audio injection or fiber signals, this already gives an error of 30m/s x 100us = 3mm. All pictures/frames, each camera provides, are in 2D.
From one picture it is not possible to state how far away the ball is from the camera. One can guess how far away by comparing the ball size relative to other objects. This does not provide mm accuracy at 20+meter distance. Calibrating the camera system takes therefore a few man-days of work. During match-day, a system operator is required. Driving the total cost up to €8000/match.

4 Thermal expansion [error estimation: 25mm]
Another effect is thermal expansion of the camera and its mounting. At 70m away from the area of interest (the goal area). A slight rotation of 0.02 degree in camera angle will cause a 25mm error / shift in the camera image. According to Hawkeye operators there is no temperature compensation when conditions change during the match or image processing re-calibration when reference objects shift. Thermal expansion of UWB anchors will cause errors below a few mm.

Kick detection [error estimation: for off-sides: 20ms]
The UWB tracker ball has internal sensors which detect kicks with 1 ms resolution. A camera system with 1000fps also has a 1ms resolution. 1000 fps camera’s to monitor the whole field with 14 x 8k camera’s would cost around 2 million euro including the server stack and software. INTEL did test this setup in a stadium in 2020.
A ball with UWB plus tracking system with 1ms resolution cost around 25k euro. A first experiment with this type of technology was conducted during the WC2022 in Qatar. Using the lower range sensor system of Kinexon in an Adidas ball center mounted sensor structure. For large stadiums it is better to use the long range pulse ball system.

CONCLUSION officiating with an optical system



Because of the sub 1000 fps update rate of the camera system, the moment of a kick is not known with the required precision to officiate off side using **VAR** (var video assistant referee).
Using **SAR** (sensor assistant referee) + VAR is a better way.
SAR can be used independent of VAR since a full 3D render of the scene is created.
The point of view can be changed during the review of the event.
The point of view of the GLT camera’s can not be changed ‘in post’.
Newer technologies like skeleTRACK try to have a variable view point during replay. This approach will still suffer from the same drawbacks as any other optical system. About 90% of the data will come from the player and 10% of the time the data is not available (occlusion) or worse is from another player (data reliability issue). Besides other effects like lighting conditions.

For further improved fan engagement, other elements like heart rate, MOx and audio are to be added. Since these features require sensors on the players, better have these sensors to incorporate tracking as well.

15mm FiFa GLT specification.
It is unlikely the Hawkeye field implementation with 12 camera's placed onto the stadium ring is within 15mm accurate for deployment as goal line technology. FiFA-accuracy criteria 15mm.
Several independent field trials comparing ChyronHego optical system in football and MLB (Major League Baseball) versus a vicon system (2mm accurate at 30m) show a typical accuracy of 25 to 80mm for short range observations. The interesting part about the '15mm' FiFa specification is the IFAB test, where the camera is placed within a few meters from the ball. An even more comprehensive 2020 study conducted by TUM (Technical University of Munich), using Tracab Gen5 versus Vicon system. Camera's placed in LOS (lign of sight), shows an error of around 287mm. See video chyronhego "Tracab optical tracking versus Vicon" timestamp: 0:18..0:28 (optical) on 30x30m
With an average error of 80mm, for a standard 'half' sport-field of 50x50m, this error will be even higher.
Similar results are also confirmed by companies providing camera based tracking like beyond-sports (acquired by Sony in 2022), sky, Swiss timing, who all have difficulties tracking sports balls and seek out sensor based systems in addition to the camera system. The key to 'believe' the hawkeye system is:
video playback and human observation are even worse so how to validate if the hawkeye conclusion is correct?

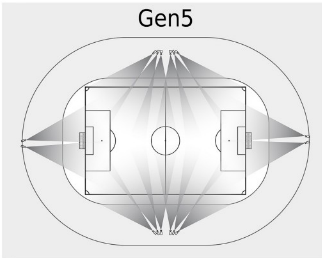
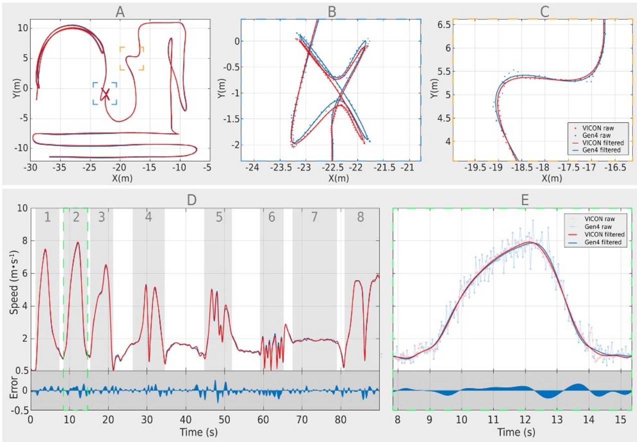


Fig 2. Spatial representation of the Gen5(1.6m height) camera architecture.



The average error of the UWB 3D ball-flight-trajectory is <20mm for a full size field. UWB measurements maintain accuracy, independent of distance.
Lower to the ground (<10cm) the error is higher mainly due to Fresnel zone effect or 'ground effect'.
The distance measurements of the pulse ball have a Gaussian noise of +/- 29mm.
The sensor from Kinexon used in the Adidas world cup ball sensor has noise level of +/-80mm. With changes over time, see page 4. Since the pulse ball has a noise which does not change over time, the static position accuracy is better. The 2022 FIFA_Kinexon Quality_Report show up to 20cm static position error (page 6).
Using 28 Kinexon anchors with a 250ms latency. This static position drift is mainly due to the change of distance over time from the DW1000 chipset. This effect can be mitigated by using a different hardware setup for the same chip, as is used in the 'pulse' ball. Static position accuracy of the pulse ball is < 10cm with the ball on the ground. Centimeter level accuracy when 'airborne' using 8 anchors around the field, 150Hz update rate, < 200ms latency.

CONCLUSION on optical GLT Hawkeye:
Adding all errors together gives a realistic accuracy of about 5cm on average in real-world stadium conditions. The referee is obliged to test the system before every match by walking backwards into the goal and check the smart-watch to see if it detected the 'goal'. In conversation with an international referee it was stated the ball need to be well within the goal to create a trigger on the watch.

COST COMPARISON optical versus UWB

x 1000 €	cost/field, team	-/match	cost p.a.	3D Accuracy 1cpk ball in flight [cm]	Accuracy 1cpk ball on ground 50m from observer [cm]	Reliability bounced shots	Latency [ms]	Data-stream Mbit/s
Hawk-Eye	300 to 500	8	12	< 5	< 15	95%(1)	<100	10000
Tracab gen 5				< 10	< 25		<200	
Pulse ball	25	-	2	< 5	< 10	98%	<200	0.5
Kinexon ball	55			< 15	< 20		<300	0.5

Links:

VICON, Chyron Hego: Tracab, validity check	2020	https://journals.plos.org/plosone/article?id=10.1371/journal.pone.0230179
Validity check of UWB handballs **INSEP**	2020	https://www.researchgate.net/publication/342851289
Ball Tracking accuracy **FRAUNHOFER**	2021	https://www.researchgate.net/publication/349465530
Validity check **FIFA** EPTS Test Report	2022	https://www.fifa.com/api/resource-hub/test-report?id=e353cafacfc04b45b79641e264e049ae
Article: withhold HawkEye payment after clanger	2022	https://www.belfastlive.co.uk/sport/gaa/gaa-urged-withhold-hawkeye-payment-24457490
Test specification GLT FiFA	2023	https://digitalhub.fifa.com/m/2adc441cd1a5e273/original/lqyuhfigvrixclnonq7o-pdf.pdf
Wiki GLT	2023	https://en.wikipedia.org/wiki/Goal-line_technology

NECESSITY for improved officiating in matches.
About 30 questionable goals per season of 380 matches occur in the Premier League.
Of which 90% are called correct by referees. In division and amature level this percentage is likely lower.
For off-sides UWB tracking is more favourable considering the 1ms detection resolution and position of ball and players legs. The disadvantage is the position of the arms and hands are not detected with radio signals, LPS. The rest of the body position and posture can be determined within 5cm accuracy using inverse kinematics. Combining the UWB position information with the position of arms and hands from cameras make a more reliable system. For officiating world-cups, leagues, division and lower classes, UWB technology is suitable. For training and performance benchmarking, UWB system clearly outperform optical systems in accuracy versus price.
Referring to camera systems which are mounted at only the center location on the field. Single POV (point of view) camera systems can not provide reliable 3D position information on the field. Combining both such systems (single POV + LPS + tracked balls) into one is cost effective and matches/exceeds the high-end Hawkeye system performance wise.

A more recent Hawkeye (owned by Sony), development is SkeleTRACK, 3D visualisation of players.
An improvement for fan engagement. As an alternative: IMU tracking sensors in the shin-guard provide sufficient data to calculate the body position via inverse kinematics. Without the need for 10 UHD, high speed cameras and a server rack to compute 2D visuals to 3D positions. Constant monitoring of all players physical load and forces on knees at a low cost for the main field and all training fields is preferred.

SUMMARY of the comparison of tier 1 players in optical vs LPS

SYSTEM	LPS, sensors + ball	Hawkeye	Notes	
Cost of installation x 1000 €	**25**	**>250**	System cost, plus installation.500K according to Jörg Schmadtke	
Operational cost per year	**2**	**25**		
All weather	**+++**	**+**	Snow, direct sun, rain, light condition affect camera systems	
Accuracy versus range	maintained	degraded		
Power consumption per year /field	solar powered	300 kWh	CO2 reduction criteria. 220.000 full size football fields in Europe	
Accuracy	<10cm	<10cm	UWB 50Hz	
Mobile system / deployment time	Yes / < 10 sec	**x**	LPS systems calibrate automatically (no training required)	
Training				
Reduce administrative load	automated	automated	Data-collection hassle for tracking, body sensors, timing gates, etc	
Progress and talent monitoring	**++**	**+**	Collect all data for all players, constantly, at an acceptable cost	
Data reliability	**98%**	**95%**	Video occlusion: not all data is actually from the athlete	
Max time, no data	< 0.1 s	> 1 s	,,	
Human body load measurement	Medical grade	best guess	Sensors placed on body are most accurate	
Fan engagement				
Body sensors (heart rate)	All integrated	2nd system		
3D	y	y	Inverse kinematics versus AI SkeleTRACK,	
Match day replay, point of view	3D, Any POV	2D, Fixed POV	Live video distribution for visitors requires too much bandwidth	
Individual performance	y		3D video with a focus on 1 player are now possible on demand	
Intrusive (sensor on shin-guard)	**yes**	**passive**	Cameras can be seen as passive observers which is preferred	
Officiating match-day				
GLT VAR accuracy	<5cm	<5cm	UWB 150Hz. Hawkeye is not mm accurate according to field trials	
Off-side VAR moment of kick	**<1ms**	**<25ms**	25ms is not suitable (no video frame of the moment of kick)	
Visuals on arms and hands	**x**	**y**		
Labor (fte required to operate)	**none**	**1 or 2**	Hawkeye cost per match around € 8000 (2022 pricing)	

Combining low cost cameras with LPS seems to be the ideal solution.

UWB Sample data GLT accuracy

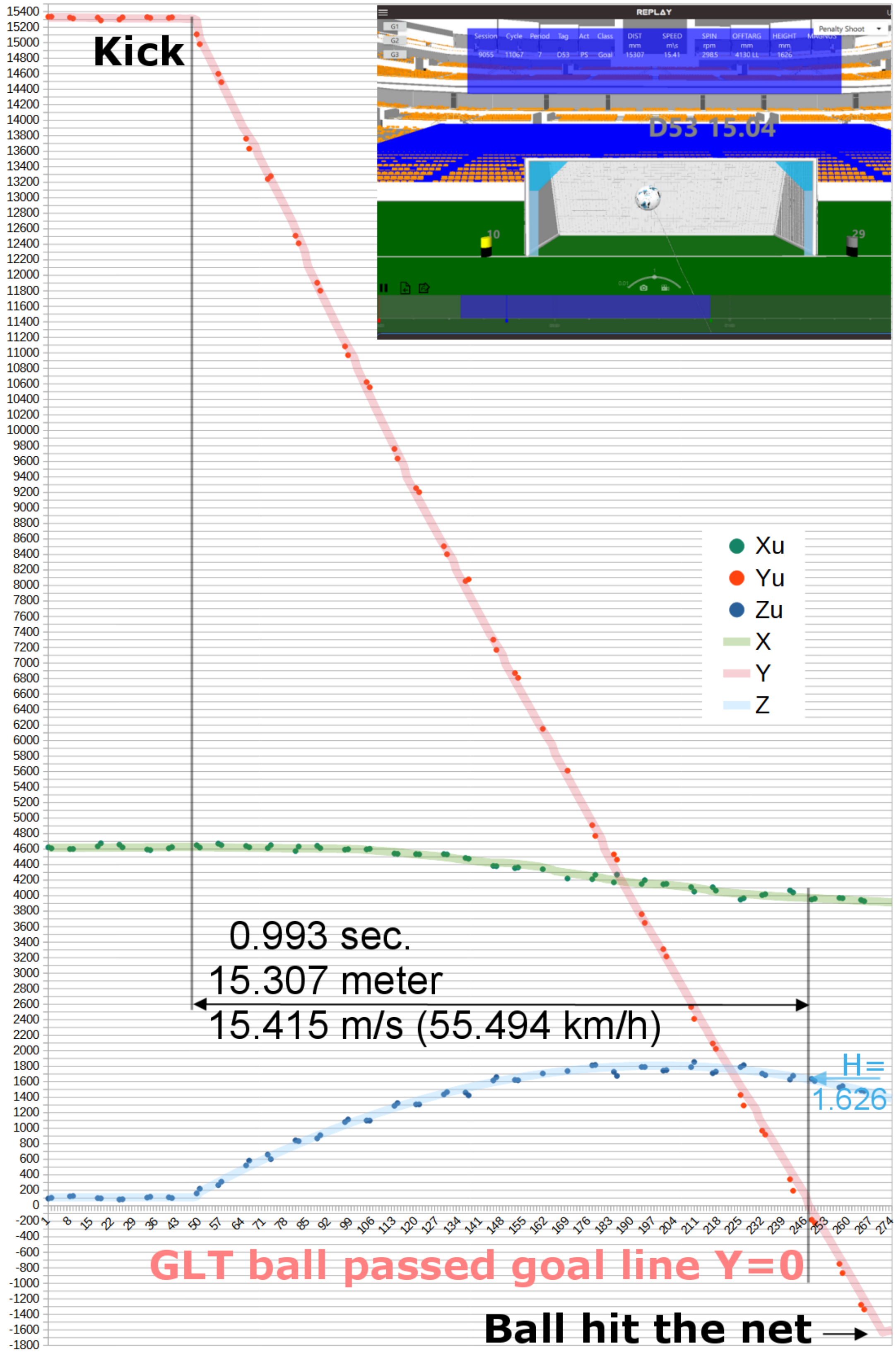
From a shot onto the goal from 15.4 meter away,
analysis of the recorded data-file and video.

3D flight path **GLT accuracy better then 5cm. Speed error <1%**
Cycle: every 80ms all recorded distances and motion capture data is forwarded to the network PC or mobile.
Period: 5ms intervals, within every cycle (200Hz sample rate)
Distance measurements in column *TOF_1..TOF_4* (time of flight) expressed in per 4.5mm units
The 3D flight path of the ball is plotted in the columns marked X Y Z in mm
The UWB measurements are recorded in columns marked Xu Yu Zu in mm, measured at a 50Hz update rate.
For match-balls this update rate is set to 150Hz.

Details of the recorded shot, see data-file:
Kick offset +3ms (after start of cycle 11055 period 0) as detected by motion capture sensor (1kHz sampling)
GLT-event (goal line technology) detected at cycle 11067, period 7
1 period earlier (cycle 11067, period 6) the ball is still 10mm before the goal line.
Kick X=4627 Y=15292 Z= 122 mm, The sensor (centered) in the ball is 110mm from the ground when idle.
GLT X=3971 Y=0 Z=1626 mm (the 3D position where the ball passed the goal line)
The distance measured over the ground = 15307mm
Time of flight (199 periods x 5ms) – 3ms offset + 0.66ms (to travel the remaining) 10mm = 993 ms
Ground speed: 15.415 m/s (55.5 km/h)
The motion capture data is placed in column Ax Ay Az for accelerometer and Gx Gy Gz for the gyroscope.
Motion capture in the ball has the unique property of measuring at the highest sensitivity over the full range
Accelerometer full range = 0 to 32G, 1G is represented as 4096 (12bit), Every sample is 18bit.
Gyro 0 to 4000 dps (degree per second). 4000 dps is about 11 revolution per second. Every sample is 19bit.
Professional football athletes can spin a ball up to max 10 rev/sec (600 rpm, revolution per minute).

UWB Sample data GLT accuracy (plotted data)

Goal line detection: ball enters goals at 162.6 cm from the ground.
Speed: 55.5 kph from 15.307m away from the goal (Y-axis in mm)
Measured 3D positions (dots) at 50Hz. At 150Hz ball tracking: 3x more samples (dots) are measured.



ROADMAP

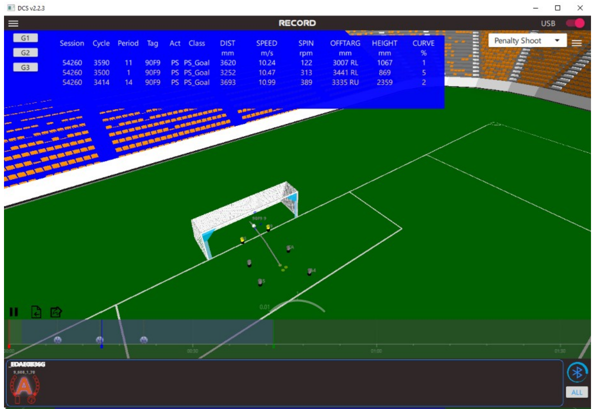
The current Pulse UWB tracked ball is in production and Kinexon is expected to go into production later in 2023. The real-world error, accuracy of both optical (hawkeye,12 cam) and radio tracked sports balls are very similar. The main difference is cost and ease of use. For wide spread adaption a significant amount of additional 3D software is needed to ensure a smooth user experience for matches, training and ball skill exercises.

3D performance software for the pulse Ball

Events are shown on the timeline. The timeline is used for replay the session from different 3D points of view.
Anchors are placed in pairs of 2, onto the field. These 2 anchors form a ‘gate’.
When placing 2 mobile field anchors more then 3 meter apart the system will detect it is a ‘goal’.
The user can identify the gates by making them blink using the 3 buttons G1 G2 G3 on the screen.
Every mobile field anchor has a powerful RGB LED panel which is clearly visible. Used for player interaction and direct performance feedback. The coordinates of the anchors are handled automatically by the system.

Free-kick/Penalty shoot

Registration of kicks
- speed of the shot
- how far off target. The target is the light blue area left and right in the goal.
- distance of the shot
- spin of the ball
- curve of the ground path of ball (as a percentage of the shot distance)
- the height of the ball when passing the goal line (GLT)



Target practice

Shoot the ball at the center of 4 field anchors at some distance away
- speed of the shot
- how far off center. When the center is hit a special light pattern will play
- distance of the shot
- spin of the ball
- curve of the ground path of ball

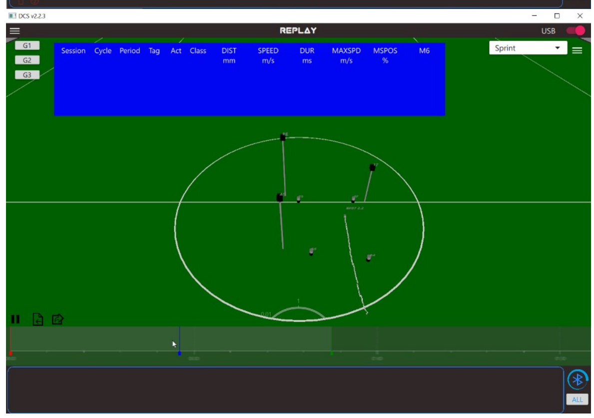
Reaction Time

When tapping on the ball a random timer is activated.
This triggers Gate1 to blink 2 to 5 seconds later.
The center point of the gate is the ‘target’ to shoot at.
- reaction time from blink to kick (*)
- how far off target
- speed of the shot

(*) The accuracy of the moment of the blink is within 60 ns ,nano seconds

Sprint

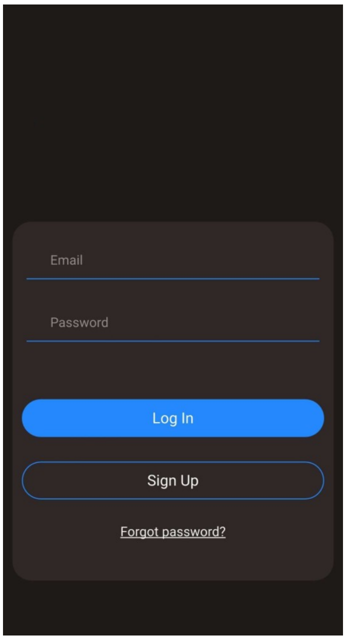
Sprint performance running between 2 gates.
- Measures the time to run between 2 gates
- The distance between the 2 gates
- Sprint speed
- Maximum speed
- At what point the maximum speed was reached as percentage of distance

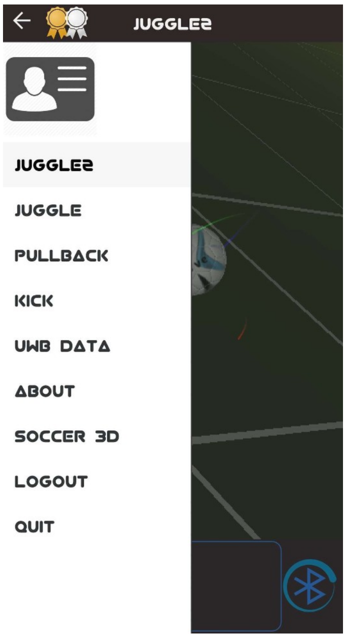


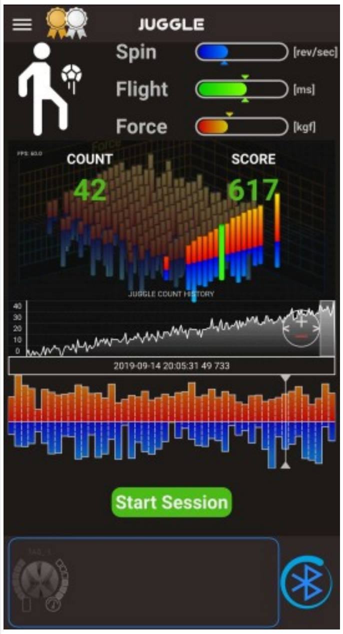
Anchors can be placed at the same height on the field or at different heights which improves the accuracy of the Z-axis values.
Accuracy of X Y position remains the same.

Mobile app

Juggle app: Juggle_App.apk





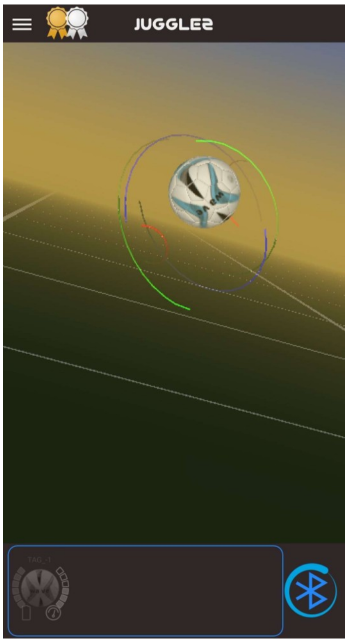


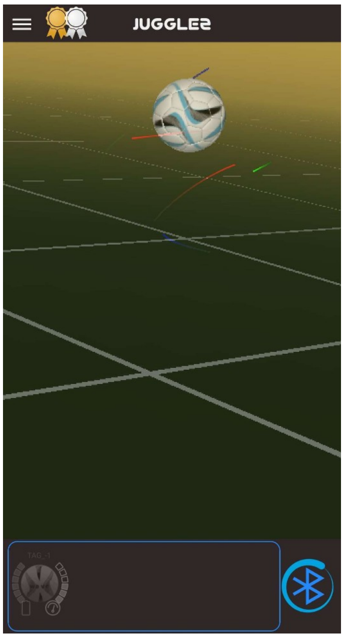
Juggle application.

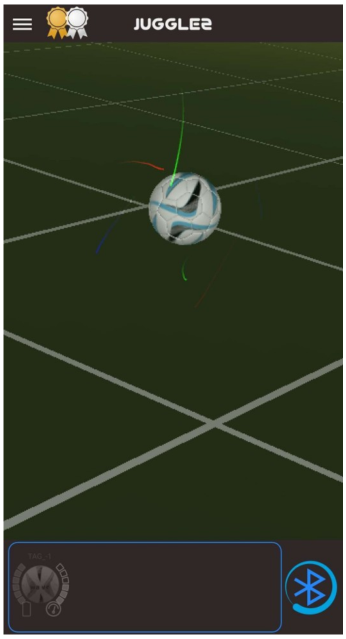
Keep the ball in the air.

- **Wave ball** ICM42686 mocap Bluetooth (no UWB tracking)
- **Pulse ball** ICM42686 mocap Bluetooth + 3D UWB tracking

1D..3D results
- results over time
- 1 finger control data-mining







point of view is controlled via the IMU in the phone

LPS Local Positioning System SPECIFICATION:

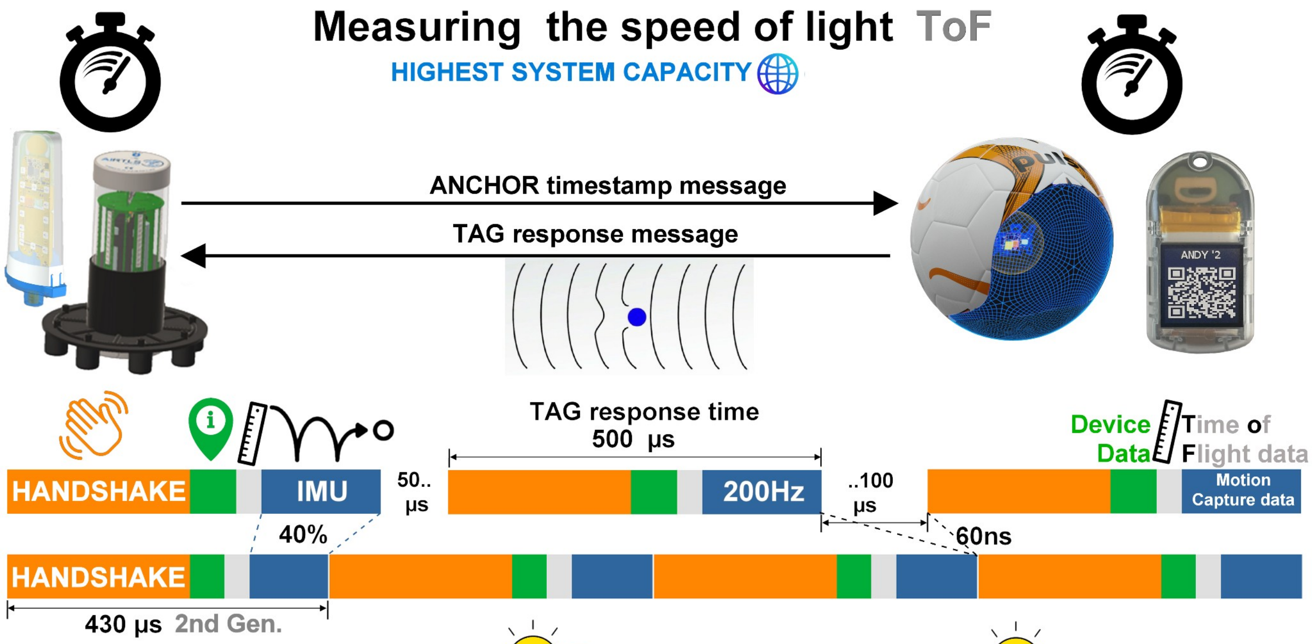
Ball tracking : UWB 3D position tracking at 150Hz (default setting 50Hz, max 1000Hz)
Motion capture 200Hz: ICM-42686 (impact detection resolution 1ms)

Player tracking : UWB 3D position tracking at 25Hz on both legs (shin-guards)
Motion capture 200Hz: ICM-42686 (impact detection resolution 1ms)

Capacity per UWB Zone of 200x100m, per UWB channel

Sport scenario (match day)	Item tracking scenario (industrial use)
2 Balls at 150Hz, mocap 1000Hz,	90000 items at 1Hz position update/zone/channel*
+ 44 players (88 tags) 25Hz, mocap 200Hz	
+ 2 referees (25Hz),	
+ 2000 assets at 0.1Hz	
all simultaneously per channel	
	Latency: <40ms @ 2800locates/sec
Latency: <200ms @ 2800locates/sec	**Latency**: average 5 sec @80k tags, 1Hz positions
Ranging: Multicast Two Way Ranging	Ranging: MTWR + TDOA
Accuracy: <8cm	Accuracy: <15cm

* Max 2 UWB channels can be active in one UWB-Zone of typically 200x200 meter(4.5 and 6.5GHz)



Locked in device FIRMWARE CODE

2nd generation UWB system specs
1 Novel Measurement Scheme:
2 Doubled capacity: 3D-Locates/second
3 Removed doppler effect.
4 Measurement speedlimit > Mach 2
5 No master clock devices required which allows 2 or more systems to be operational on the same field

Low entropy near lossless fixed length IMU (motion capture) data compression

> 15% capacity increase

Time Sensitive Networking UWB Distributed synchronisation

> 10% capacity increase

APPLICATIONS

Fan engagement

Live streaming of heart rate data, player performance, game statistics, 3D replay and the ball.
Ball data contains: speed, spin, curve and 3D path.

Metaverse: real-world gaming, AI

Collected player data about endurance, tactical insights (AI behavioural modelling) and passing skills make a ‘digital’ twin of every player. Play against the next weekend opponent as a console game yourself or have AI showcase the best strategy.

Match officiating

Accuracy of the ball position is within official FiFA GLT (goal line detection) criteria.
The referee tag has a display and haptic feedback.

Skill training and personal development

The mobile tracking system fits inside a small bag.
An all in 1 tool replacing timing gates, stopwatches and guesswork.
Many players and balls are tracked and recorded at the same time.
Classic training exercises and training matches are now recorded in 3D to show where to improve.
Sprint performance also registers top-speed which timing gates can not provide.
The ball sensors analyse juggle performance even without a UWB tracking system present, ideal for training at any place. Personal and team development is also assessed using questionnaires.

Social media

Share video clips in 3D of the best performance on social media
Annotate performance and share analytics between coach and players
Review performance from any angle in 3D

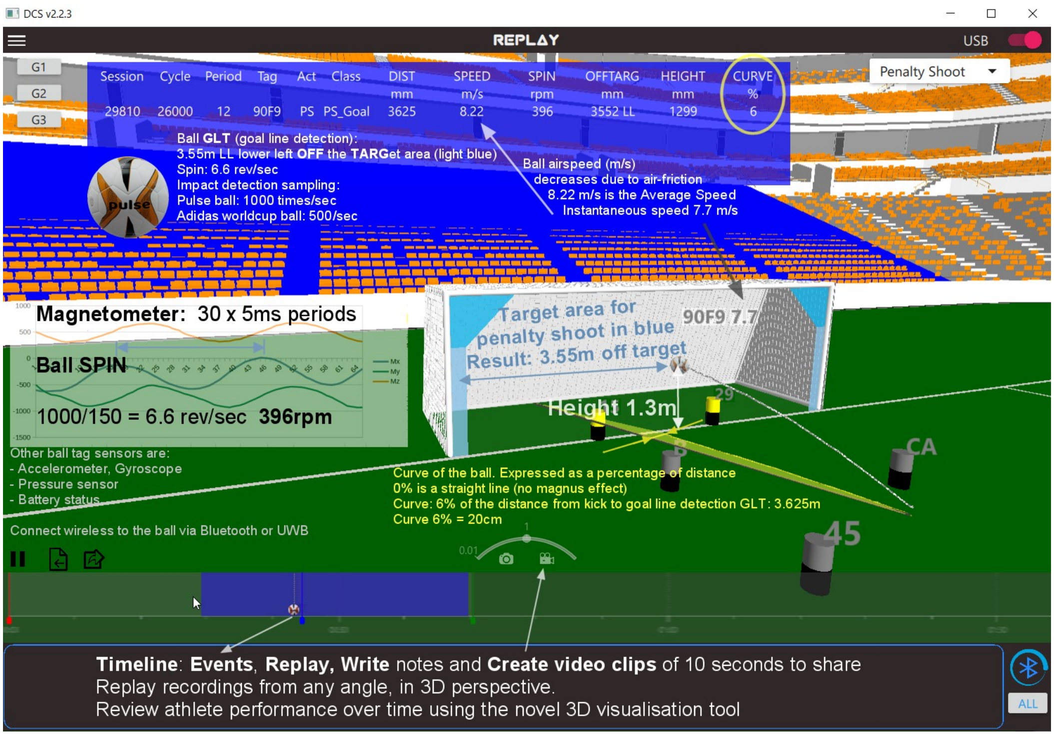
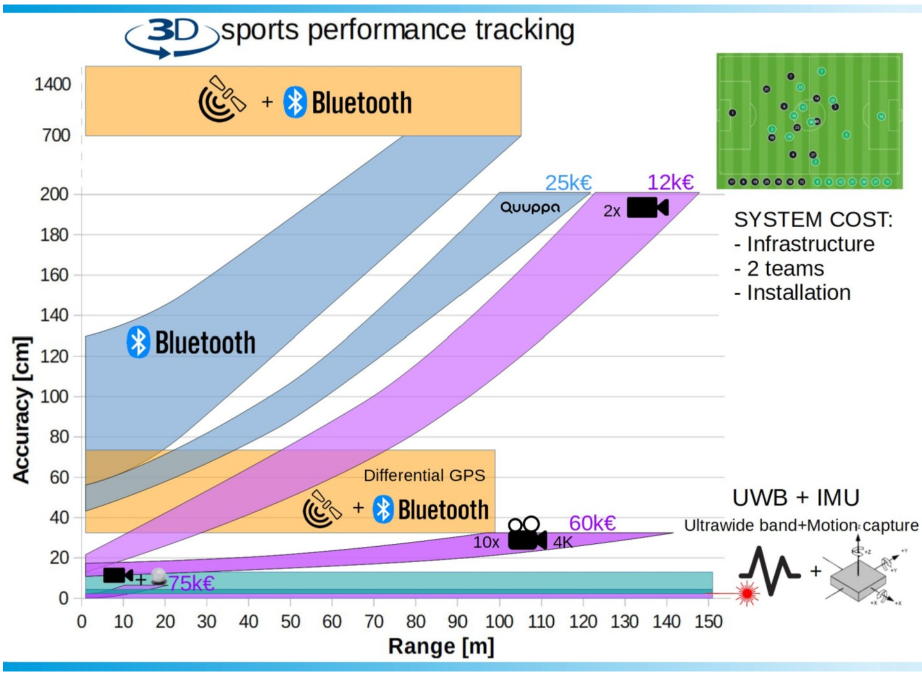


Fig 7: 3D software explained

Tracking technologies

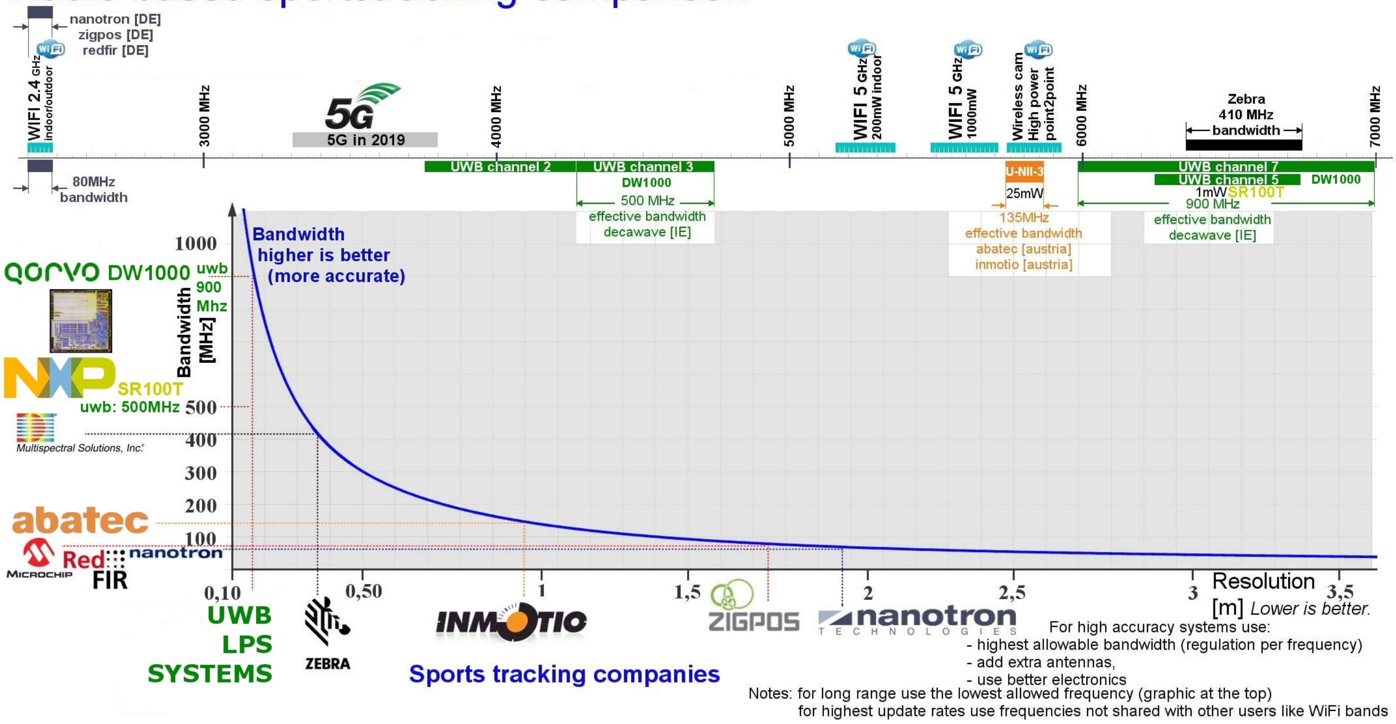
Accuracy, range and cost for 1 soccer-field and 22 players for different tracking technologies



Only lasers, UWB, differential GPS and motion capture technology maintain their accuracy when range, distances increases. Optical tracking system have issues with reliability of accuracy because of obstructed views in multiplayer / multi tag environments which yields typically about 10% false data/mixed-up data.

	Accuracy [cm]	Accuracy [cm]	Reliability [%] of tracked objects		Cost x1000 €
	@ 20m distance	@ 100m distance			(approx.)
GPS, GNSS	300	300	90		20
Bluetooth®	500	1500	70	Bluetooth® reconnect issue and inaccuracy at longer distances	20
CAMERA (reflective balls)	**0.1**	-	99.99	Fixed cam close to target only 1 object to track (Vicon)	76
CAMERA (AI) Using at least 10 cameras	**5**	30	90	90% Mainly because of blocked view	35
UWB 1 tag in neck (C6-bone)	**10**	**10**	**96**		16
UWB 2 tags on lower legs	**8**	**8**	**98**		22
UWB + IMU	**< 5**	**< 5**	**99**	Sensor fusion,UWB IMU fusion and inverse kinematics	25
UWB + IMU + CAMERA	**5**	**5**	**99**	Sensor fusion,UWB IMU fusion and inverse kinematics + camera	35

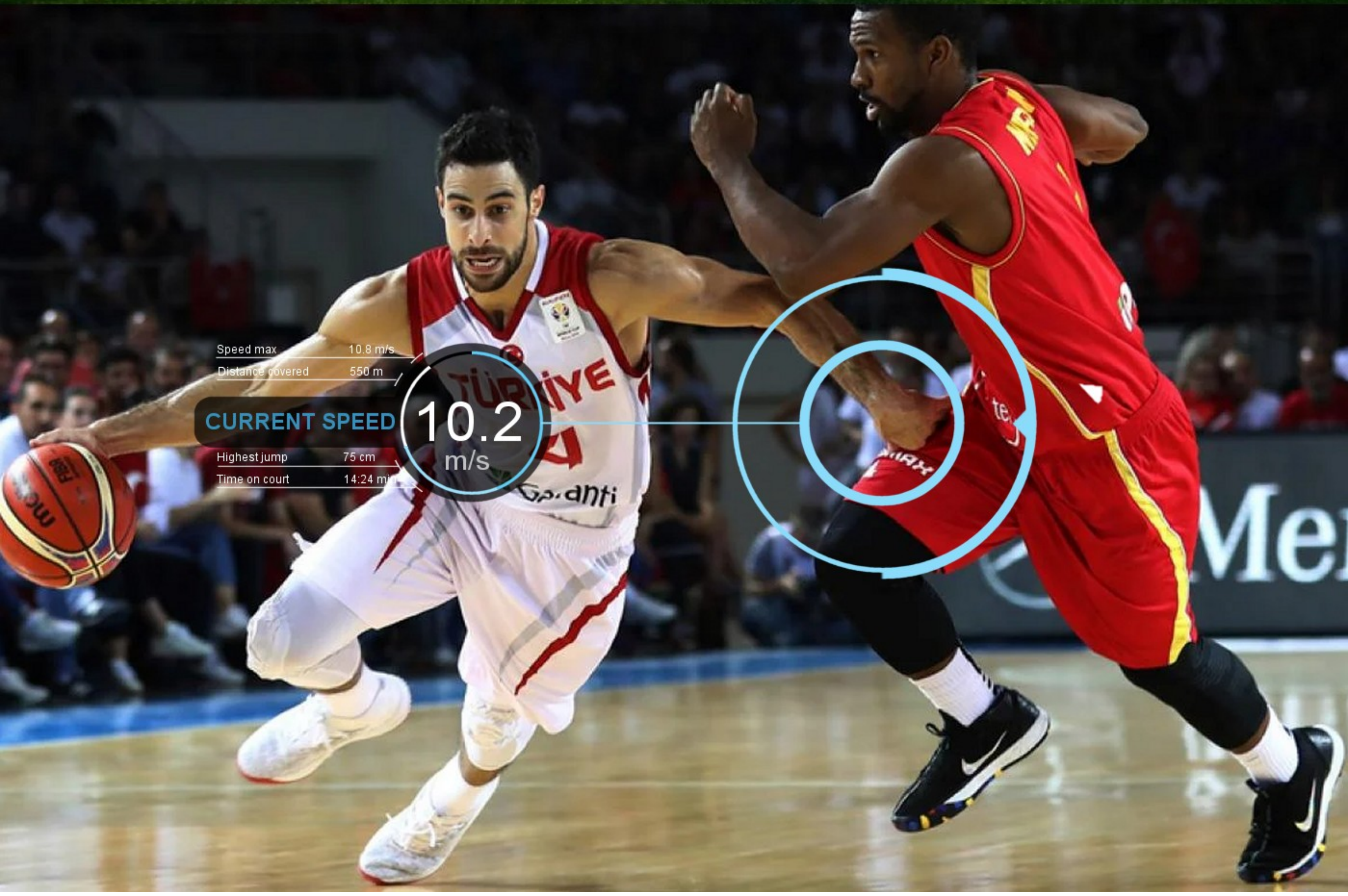
Radio based sportstracking comparison



Relation between used radio bandwidth, and accuracy vs. chip suppliers vs. tracking companies.
Most sport tracking LPS companies use license free frequencies outside the frequency bands used for WiFi to avoid interference. Ultra-wideband uses 2 channels which can be found at the top of the figure in green.
UWB Channel 3 between 2.4GHz-WiFi and 5Ghz-WiFi centered around 4.5GHz (4500 MHz).
UWB Channel 5 with 900Mhz bandwidth centered around 6.5GHz.
On the graphics below the frequency spectrum it shows, based on radio physics:
A bandwidth of 900MHz results in about 10cm accuracy.

When using more advanced electronics and design the accuracy in ‘line of sight’ conditions is +- 2.9cm (1 standard deviation) for UWB. The measurement ‘noise level’ of +- 2.9cm is the same for all distances between 0 and 300m. The above plot shows, based on the laws of physics, a high bandwidth is required to achieve high accuracy. Radio technologies operating on the WiFi bands are allowed to have a bandwidth of only 20, 80 or 135Mhz which limits the accuracy. Shown in the light-blue ‘blocks’ in the radio spectrum of the above picture.

Sport Tracking LPS Vendor	Chipset	ChipBrand		**Bandwidth** [MHz]	**Accuracy** [cm]
Since 2014 the accurate DW1000 is used in all modern LPS systems	**DW1000**	Decawave Qorvo	IE USA	500 or 900	<10
	SR100T	NXP	NL	500	
	U1 TMKA75	Apple	USA	500	
Inmotio (sci sport)	Analog design	**Abatec**	AT	135	>30
Nanotron	NanoLoc	Nanotron	DE	80	>50
Zigpos	RF233	Atmel	DE	80	>50
Fraunhofer	RedFIR in ball	RedFIR	DE	80	>50



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