INDIAN INSTITUTE OF TECHNOLOGY GANDHINAGAR

NATURE INSPIRED COMPUTING

Date of Examination: 03 May 2019, 09.00 PM

Full Marks: 25

(Time allowed: 150 minutes)

Note: *Read the question carefully before answering. Some events and incidents described in this question paper are either the products of the instructor's imagination or used in a fictitious manner. Some portions of the questions are copied verbatim from the sources mentioned. However "quotes" have been avoided in the question paper to maintain of thought. In case of mismatch in sampling frequencies, please design and implement suitable sample rate conversion systems. Make suitable logical assumptions, where ever necessary. Answer all parts of a question at the same place and clearly show the steps followed.*

1. Accomplishing what was previously thought to be impossible, a team of international astronomers has captured an image of a black holes silhouette. Evidence of the existence of black holes mysterious places in space where nothing, not even light, can escape has existed for quite some time, and astronomers have long observed the effects on the surroundings of these phenomena. In the popular imagination, it was thought that capturing an image of a black hole was impossible because an image of something from which no light can escape would appear completely black. For scientists, the challenge was how, from thousands or even millions of light-years away, to capture an image of the hot, glowing gas falling into a black hole. An ambitious team of international astronomers and computer scientists has managed to accomplish both. Working for well over a decade to achieve the feat, the team improved upon an existing radio astronomy technique for high-resolution imaging and used it to detect the silhouette of a black hole outlined by the glowing gas that surrounds its event horizon, the precipice beyond which light cannot escape. Learning about these mysterious structures can help students understand gravity and the dynamic nature of our universe, all while sharpening their math skills. Though scientists had theorized they could image black holes by

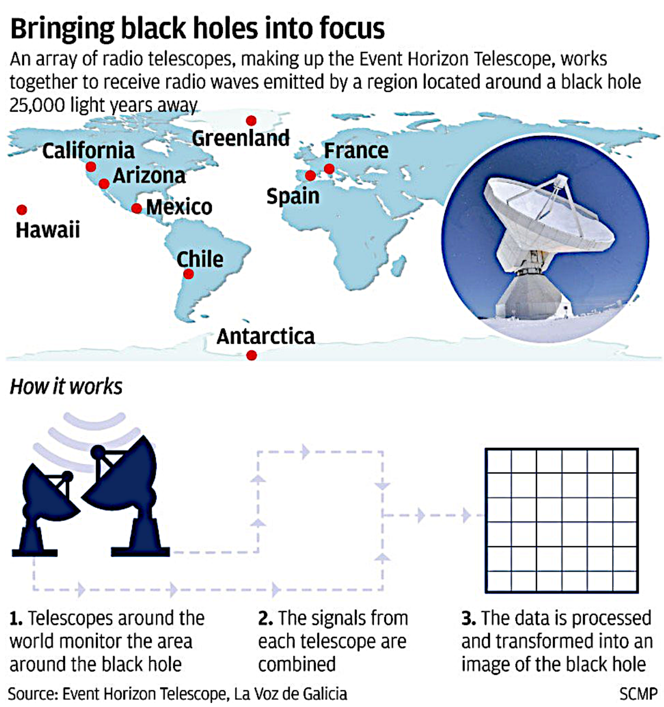

Figure 1

capturing their silhouettes against their glowing surroundings, the ability to image an object so distant still eluded them. A team formed to take on the challenge, creating a network of telescopes known as the Event Horizon Telescope, or the EHT. They set out to capture an image of a black hole by improving upon a technique that allows for the imaging of far-away objects, known as Very Long Baseline Interferometry, or VLBI. Telescopes of all types are used to see distant objects. The larger the diameter, or aperture, of the telescope, the greater its ability to gather more light and the higher its resolution (or ability to image fine details). To see details in objects that are far away and appear small and dim from Earth, we need to gather as much light as possible with very high resolution, so we need to use a telescope with a large aperture. Thats why the VLBI technique was essential to capturing the black hole image. VLBI works by creating an array of smaller telescopes that can be synchronized to focus on the same object at the same time and act as a giant virtual telescope. In some cases, the smaller telescopes are also an array of multiple telescopes. This technique has been used to track spacecraft and to image distant cosmic radio sources, such as quasars. The aperture of a giant virtual telescope such as the Event Horizon Telescope is as large as the distance between the two farthest-apart telescope stations for the EHT, those two stations are at the South Pole and in Spain, creating an aperture thats nearly the same as the diameter of Earth. Each telescope in the array focuses on the target, in this case the black hole, and collects data from its location on Earth, providing a portion of the EHTs full view. The more telescopes in the array that are widely spaced, the better the image resolution. EHT has a target tracking scheme, which can be set to keep the focus on a particular object under consideration. Propose a neural network based mechanism to achieve this target tracking. The tracking scheme must not react to sudden changes in the desired target location, which can occur only due to human or communication error. It may also be noted that the desired trajectory is non-linear in nature with different non-linearities depending on orientation of Earth and location of EHT. Derive all the update rules assuming the neural network as one using a convex combination of a FLANN, an RBF and a adaptive second order Volterra network. In addition, formulate the above mentioned neural network update as an evolutionary computing algorithm based optimization task. To test VLBI for imaging a black hole and a number of computer algorithms for sorting and synchronizing data, the Event Horizon Telescope team decided on two targets, each offering unique challenges. The closest supermassive black hole to Earth, Sagittarius A*, interested the team because it is in our galactic backyard at the center of our Milky Way galaxy, 26,000 light-years (156 quadrillion miles) away. (An asterisk is the astronomical standard for denoting a black hole.) Though not the only black hole in our galaxy, it is the black hole that appears largest from Earth. But its location in the same galaxy as Earth meant the team would have to look through pollution caused by stars and dust to image it, meaning there would be more data to filter out when processing the image. Nevertheless, because of the black holes local interest and relatively large size, the EHT team chose Sagittarius A* as one of its two targets. The second target was the supermassive black hole M87*. One of the largest known supermassive black holes, M87* is located at the center of the gargantuan elliptical galaxy Messier 87, or M87, 53 million light-years (318 quintillion miles) away. Substantially more massive than Sagittarius A*, which contains 4 million solar masses, M87* contains 6.5 billion solar masses. One solar mass is equivalent to the mass of our Sun, approximately 2×10^3 kilograms. In addition to its size, M87* interested scientists because, unlike Sagittarius A*, it is an active black hole, with matter falling into it and spewing out in the form of jets of particles that are accelerated to velocities near the speed of light. But its distance made it even more of a challenge to capture than the relatively local Sagittarius A*. As described by Katie Bouman, a computer scientist with the EHT who led development of one of the algorithms used to sort telescope data during the processing of the historic image, its akin to capturing an image of an orange on the surface of the Moon. By 2017, the EHT was a collaboration of eight sites around the world (Figure 1) and more have been added since then. Before the team could begin collecting data, they had to find a time when the weather was likely to be conducive to telescope viewing at every location. The telescope in Chile needs a cooling mechanism to ensure that the core of the telescope is maintained within 25 to 30 degree Celsius and temperature in Chile can vary from 3 degrees to 35 degrees. Heavy winds can also impact the temperature at the core. Design a Fuzzy controller for this task using atleast 2 input variables and five rules with an OR operation between the two fuzzy variables. Estimate the fan speed of the temperature controller using the above designed mechanism for an outside temperature of 32 degrees and wind speed of 60 kmph. Use a suitable de-fuzzification method, clearly stating the de-fuzzification method used. Clearly draw ALL the fuzzy rules. For M87*, the team tried for good weather in April 2017 and, of the 10 days chosen for observation, a whopping four days were clear at all eight sites! Each telescope used for the EHT had to be

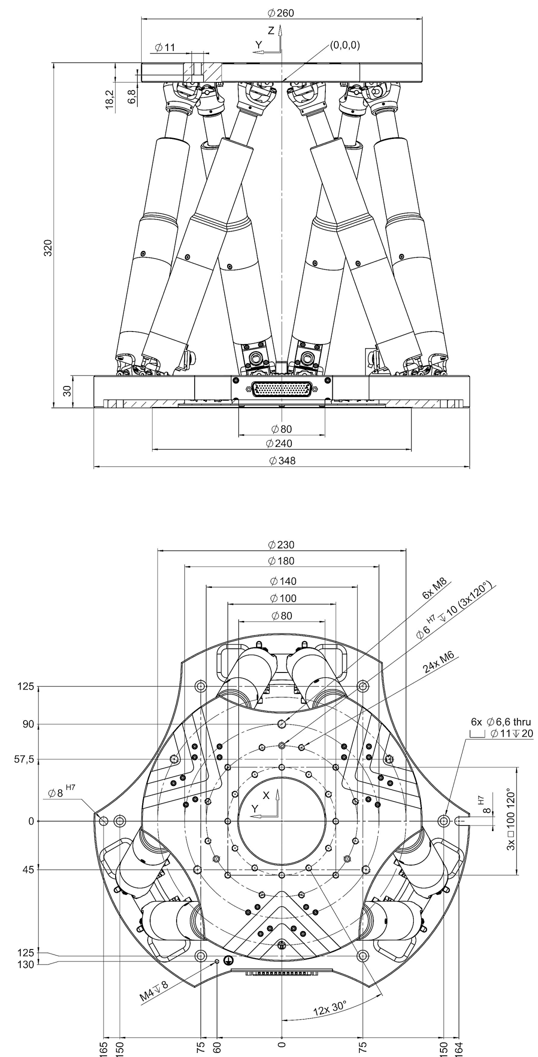

Figure 2

highly synchronized with the others to within a fraction of a millimeter using an atomic clock locked onto a GPS time standard. This degree of precision makes the EHT capable of resolving objects about 4,000 times better than the Hubble Space Telescope. To ensure this precision, each telescope is mounted on a 6-DOF hexapod similar to the one shown in Figure 2. The hexapod has a control mechanism, which measures small ground vibrations and move the six legs of the hexapod to make sure that the telescope is precisely kept at a desired orientation. Propose a control mechanism for the hexapod with suitable update rules. As each telescope acquired data from the target black hole, the digitized data and time stamp were recorded on computer disk media. Gathering data for four days around the world gave the team a substantial amount of data to process. The recorded media were then physically transported to a central location because the amount of data, around 5 petabytes, exceeds what the current internet speeds can handle. At this central location, data from all eight sites were synchronized using the time stamps and combined to create a composite set of images, revealing the never-before-seen silhouette of M87*s event horizon. The team also has real-time hexapod status from all the sites. The hexapod generates a code [000000] if all the six legs of the hexapod are accurately following the command of the previously designed control mechanism. Error or non-compliance with the controller will create an error code with '1' corresponding to the arm with the error code. For example, if the second leg of a hexapod is not following the commands of the controller, an error code [010000] is generated. Error at two adjacent legs can badly affect the final image generation and the data point from such a station must not be considered. Propose a simple neural network scheme using Hebbian learning which can generate a warning signal if two adjacent legs of a hexapod are not following the command. How is lateral inhibition implemented in competitive learning? The team is also working on generating an image of Sagittarius A* from additional observations made by the EHT. As more telescopes are added and the rotation of Earth is factored in, more of the image can be resolved, and we can expect future images to be higher resolution. To complement the EHT findings, several NASA spacecraft were part of a large effort to observe the black hole using different wavelengths of light. As part of this effort, NASAs Chandra X-ray Observatory, Nuclear Spectroscopic Telescope Array (NuSTAR) and Neil Gehrels Swift Observatory space telescope missions all designed to detect different varieties of X-ray light turned their gaze to the M87 black hole around the same time as the EHT in April 2017. NASAs Fermi Gamma-ray Space Telescope was also watching for changes in gamma-ray light from M87* during the EHT observations. If the EHT observed changes in the structure of the black holes environment, data from these missions and other telescopes could be used to help figure out what was going on. Though NASA observations did not directly trace out the historic image, astronomers used data from Chandra and NuSTAR satellites to measure the X-ray brightness of M87*s jet. Scientists used this information to compare their models of the jet and disk around the black hole with the EHT observations. The X-ray brightness data is send to Earth station as discrete signal values at 2000 samples per second. Due to malfunctioning of the on-board power supply system, the satellite's on-board computer decides to compress the data before sending it to the Earth station. Design a neural network based mechanism which can compress this data to 500 samples per second and recover the data at the Earth station without any degradation (Attn EE students - This is not DSP! So no Upsampling/Downsampling please!). Other insights may come as researchers continue to pore over these data. Learning about mysterious structures in the universe provides insight into physics and allows us to test observation methods and theories, such as Einsteins theory of general relativity. Massive objects deform spacetime in their vicinity, and although the theory of general relativity has directly been proven accurate for smaller-mass objects, such as Earth and the Sun, the theory has not yet been directly proven for black holes and other regions containing dense matter. One of the main results of the EHT black hole imaging project is a more direct calculation of a black holes mass than ever before. Using the EHT, scientists were able to directly observe and measure the radius of M87*s event horizon, or its Schwarzschild radius (A Schwarzschild radius is the radius of the boundary of a black hole), and compute the black holes mass. That estimate was close to the one derived from a method that uses the motion of orbiting stars thus validating it as a method of mass estimation. The size and shape of a black hole, which depend on its mass and spin, can be predicted from general relativity equations. General relativity predicts that this silhouette would be roughly circular, but other theories of gravity predict slightly different shapes. The image of M87* shows a circular silhouette, thus lending credibility to Einsteins theory of general relativity near black holes. The data also offer some insight into the formation and behavior of black hole structures, such as the accretion disk that feeds matter into the black hole and plasma jets that emanate from its center. Scientists have hypothesized about how an accretion disk forms, but theyve never been able to test their theories with direct observation until now. Scientists are also curious about the mechanism by which some supermassive black holes emit enormous jets of particles traveling at near light-speed. These questions and others will be answered as more data is acquired by the EHT and synthesized in computer algorithms.

(*Courtesy: Wikipedia, NASA, vox.com, physikinstrumente.com, SAO/NASA Astrophysics Data System (ADS)*) (25 marks)
